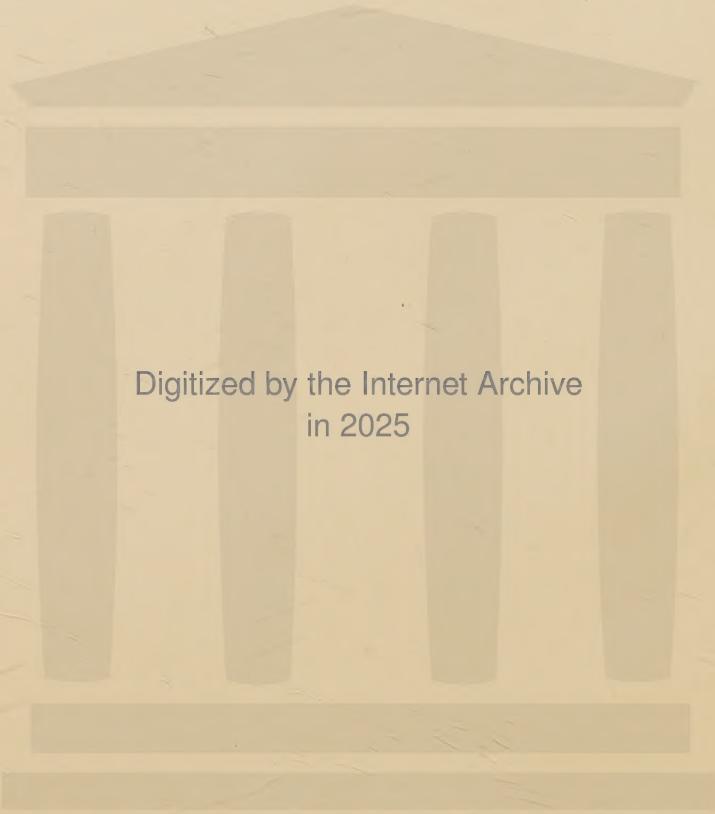


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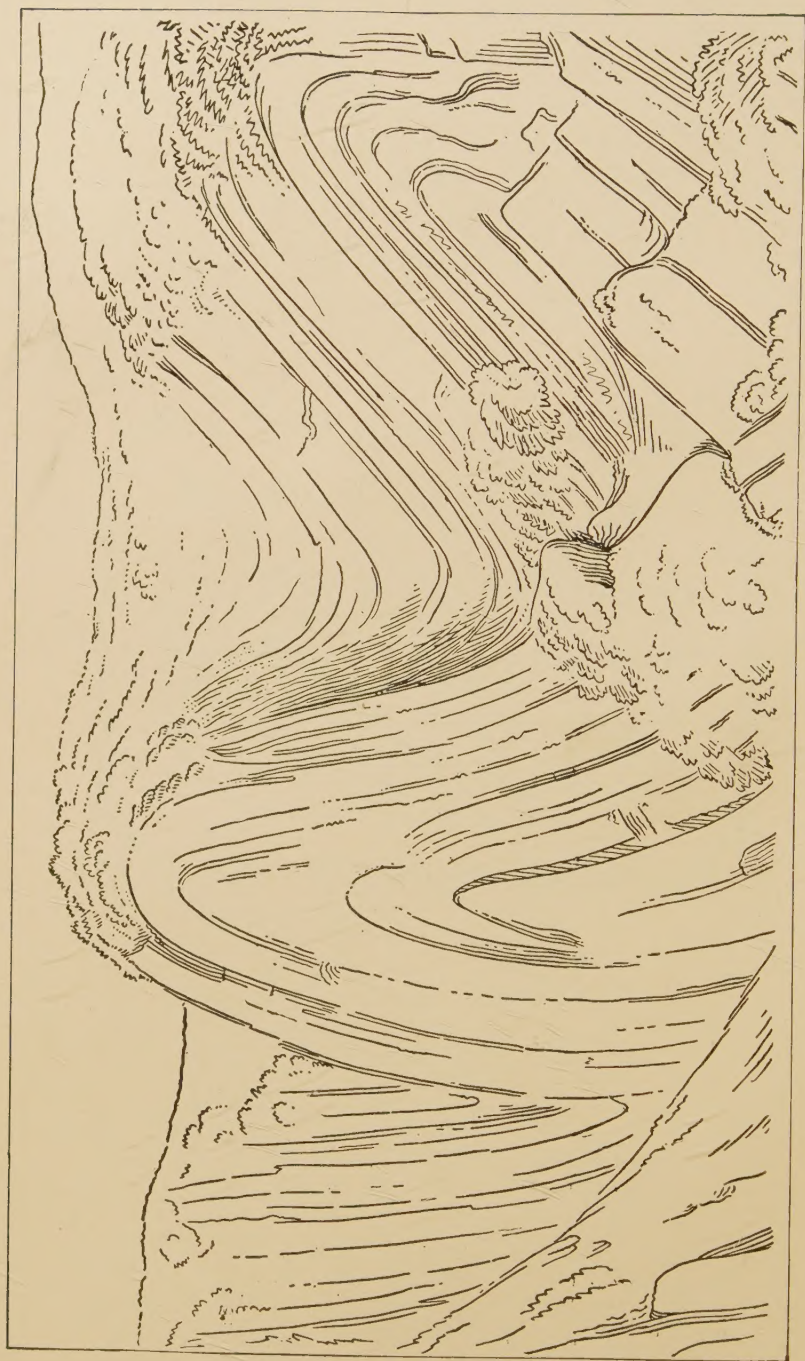
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GEOLOGIC STRUCTURES

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Contorted strata on the coast of Berwickshire, Scotland. (After Sir James Hall, Bart. 1812).

(Frontispiece)

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GEOLOGIC STRUCTURES

BY
BAILEY WILLIS

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SECOND IMPRESSION

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PREFACE

THE purpose of this book is to describe geologic structures and to apply the principles of mechanics to their interpretation. The work is in some sense a technical and advanced study, and yet it is possible that the effort which has been made to present the subject simply, in English rather than in Geology, may be successful to the extent of throwing light on the subject for the untechnical reader as well as for the special student.

To G. K. Gilbert, who thirty-eight years ago suggested the study of the mechanical principles underlying structural geology, I owe my introduction to the subject. The "Mechanics of Appalachian Structure" was inspired by him. To the great Swiss geologist, Albrecht Heim, I. together with many colleagues, owe the recognition of the fact that he laid the corner-stone of our work in "Das Mechanismus der Gebirgsbildung." To C. R. Van Hise and to many colleagues still living I am indebted for more helpful suggestions than I can acknowledge. For the views here advanced, however, in so far as they may present any novelty, I alone am responsible.

BAILEY WILLIS.

SANTIAGO DE CHILE,
May, 1923.

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3 GEOLOGIC STRUCTURES

SECTION I

DESCRIPTIONS OF ROCK STRUCTURES

CHAPTER I

STRATIFICATION

Definition.—Stratification is that original structure which divides sediments into beds, layers, or strata. The structural unit of stratified rocks is a bed, a layer, or a stratum. It has great extent in all directions in one plane, but perpendicular to that plane it has very slight thickness. The extent is measurable in miles, the thickness only in feet, inches, or fractions of inches.

In common usage the term bed or stratum is applied to a division which has a thickness of a few inches or feet. Layer is used to describe thinner divisions. *Laminæ* are layers of the thickness of paper.

Stratification is the result of interruptions in the process of accumulation of sediment. It is therefore a character imposed upon the sediment as it accumulated, and is an original inherent characteristic.

Bedding is a term of broader application than stratification, since it is not limited to sediments, but is used as pertinently to describe the structure of igneous or metamorphic rocks, such as tuffs, lavas, granites, gneisses, or schists, when these rocks occur in layers of greater or less thickness. Bedding may be due to any one or to several of a number of diverse conditions, to be described in their appropriate context.

Neither stratification nor bedding can be used properly in connection with the effects of mechanical pressure, to which the terms jointing, cleavage, or fissility apply. Nor is the development of shelly layers in consequence of chemical alteration a form of stratification.

The Origin of Stratification.—Sediments are distributed by currents of air and water, and are deposited over wide areas in relatively thin masses. They thus form strata, the structural unit of stratified rocks. Strata then owe their existence to deposition, and as long as deposition is continuous the result is a stratum. But when deposition is interrupted that stratum is finished, and another may be spread over the first only when deposition is renewed. It is thus evident that stratification originates in discontinuous or interrupted settling of sediments from currents of air or water.

The upper surface of any one stratum is in contact with the lower surface of the succeeding stratum along a plane which is called a bedding plane. It is a flat or gently curved surface which, in its original attitude, may be nearly or quite horizontal, but may also, under certain conditions of deposition, as on the face of an embankment, be formed in an inclined position. We shall see later that strata may be warped or bent and thus may assume inclined positions quite different from their original attitude.

Varieties of Stratification.—Stratification may be obscure or distinct. For instance, if the sediment be coarse sand, the surface of the deposit is rough, and even though sedimentation be interrupted a later deposit of similar sand interlocks with that previously laid down, leaving only an obscure bedding plane. There is a tendency to massiveness in sandstones, and when that is not the case any evident bedding is commonly due to alternations of strata of sand with thin layers of clay.

Stratification in shale is often not obvious to the eye, the material being homogeneous, but it is mechanically well defined. Interruptions are apt to be frequent during the deposition of mud, and the surface of the deposit may harden or may be scoured by currents capable of removing loose material. There is then an absence of bond between the earlier and later accumulations, and their plane of contact becomes a plane of splitting. Shales are characteristically thin-bedded and split readily on the bedding planes. Weathering often brings out the tendency to split or

accentuates differences of color, but chemical alteration may result in deceptive similar appearances which actually lie at angles to the original stratification.

Limestones accumulate as calcareous muds in depths which are often below the reach of superficial currents. They are, therefore, less liable to interruption of deposition than muds and sands accumulating in shallower water. Pure limestones are, therefore, relatively thick-bedded. Limestone deposits do, nevertheless, suffer interruption and scour in shallow seas, and they then exhibit well-defined stratification. Earthy limestones are frequently interbedded with shale, and the individual strata may alternate with each other in thin and oft-repeated layers.

Stratification is most obvious where strata differ in grain, color, or composition. Alternations of finer and coarser sands, of sand and shale, or of limestone and shale are of common occurrence, the individual strata being but a few inches or a few feet thick, although their aggregate may attain many hundred feet in thickness. Inasmuch as the change in character is due to a more or less complete change in sediment, each bedding plane is a surface on which the bond is weak. Stratification of this kind is, therefore, not only obvious but mechanically well defined. The strata separate readily on the bedding plane, and if subjected to appropriate forces they will slip past one another on the bed. Such masses are therefore flexible.

Dimensions of Strata.—Any stratum is a lens. It is commonly a lens of very large diameters as compared with its thickness, and this disproportion in dimensions has an important bearing on the resistance which it offers when it is subjected to pressure in earth movements. The dimensions of strata affect their rigidity or flexibility and determine their manner of yielding. The size of lenses is important from another point of view, for porous strata are the reservoirs in which water, oil, and gas gather.

To obtain some idea of the dimensions attained by strata we may glance at some of the original structures which are built up by their accumulation. The alluvial cone is formed of innumerable lenses of coarser and finer conglomerate, sands, and clays, distributed irregularly throughout the mass. No single stratum extends far. The diameters are a few hundred or a few thousand feet, and the thicknesses a few inches to a score of feet. In desert basins the slopes which extend from the base of the moun-

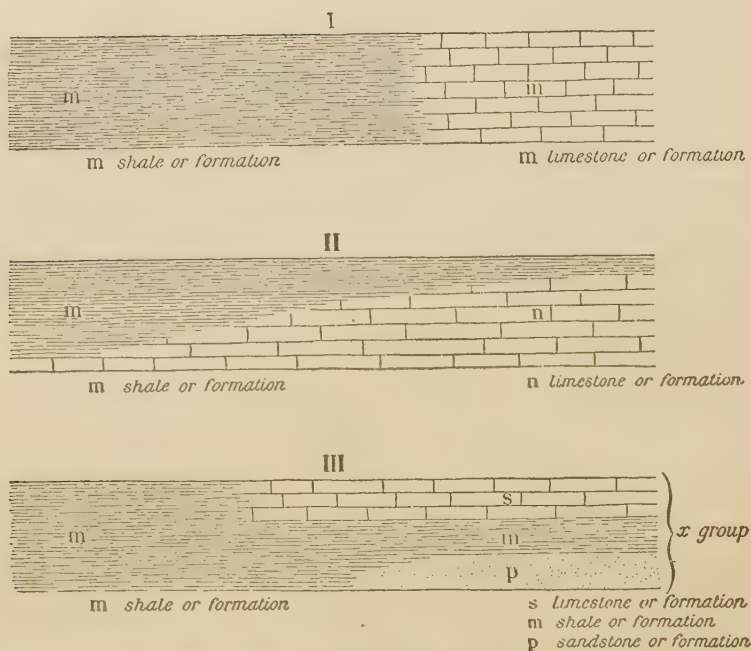
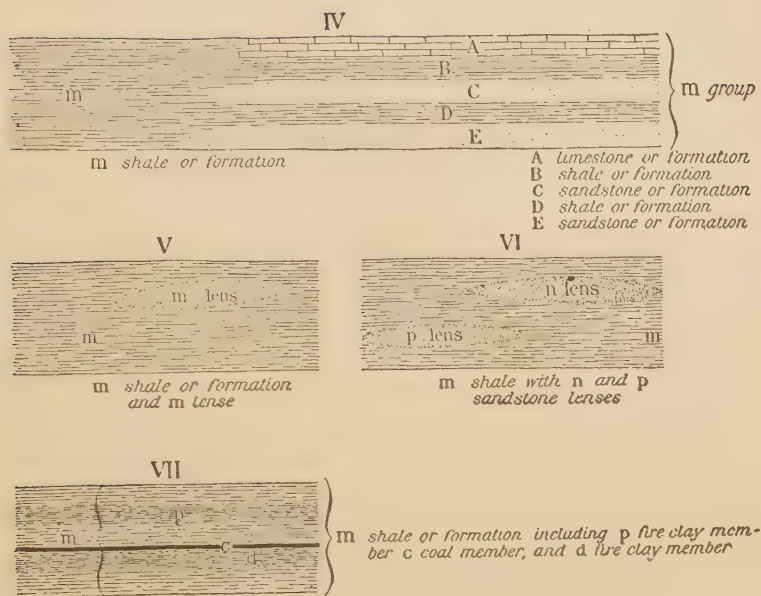


FIG. 1.—Lithologic Units. Part I shows the *m* shale passing into a limestone which retains identical stratigraphic associations. Being exactly continuous stratigraphic units, they should retain the same geographic name on grounds of convenience and simplicity.

Part II shows the *m* shale grading into a limestone with prolonged overlap, so that the two rocks must be discriminated in one area. Not only are they lithologically different but they have different stratigraphic associations, and they should receive distinct geographic names; *m* shale and *n* limestone.

Part III shows the *m* shale continuing as an individual with reduced thickness into new stratigraphic associations. Individuality is not dependent on thickness nor on stratigraphic association only; it is determined by continuity, and the formation may retain its name, *m* shale. But the group *pms* cannot then be called the *m* group, because *m* would have two meanings, one for a simple part, and one for a complex whole.



Part IV shows the *m* shale replaced by five formations, two of which, *B* and *D*, are shales like it. Individuality is here lost in multiplicity. Neither *B* nor *D* can be distinguished as representing *m*, which must, accordingly, give way where they divide into two. The complex *ABCDE* may be called the *m* group, since it has equivalent stratigraphic associations with *m*.

Parts V and VI illustrate the occurrence and naming of local lenses in a formation where such divisions are not of sufficient extent to justify a distinct series of names for the lens and the parts of the formation above and below it. One lens may receive the formation name, but two or more must be named distinctly.

Part VII presents the case of a formation which is the least practicable lithologic individual for mapping, but which includes fractional parts that are important in discussion. The fractional character of the parts may be indicated by calling them members, each member being given a distinctive geographic name.

tains consist of alluvial fans that often merge into one another and possess similar internal structures in their upper portions, but further out from the ranges become more uniform in texture and consist of more extensive lenses. The alluvium of a great river like the Mississippi is very widespread, but within narrow limits is also very variable. The strata of fine sand and clay, which are distributed by winds or floods over an intermontane basin like that of Great Salt Lake, or the lacustrine deposits of large lakes are among the most widespread and uniform of continental formations.

Beach and along-shore deposits are commonly long and narrow, after the pattern of coastal features. Exceptions to this rule are found in extensive sediments which represent migrating conditions, such, for instance, as the Trinity sands that mark an advance of the waters of the Gulf of Mexico over eastern Texas and Oklahoma.

If we turn to the fine, muddy sediments of epicontinental seas, of which Hudson Bay is an existing example, and beneath which practically all of the continents have at one time or another been submerged, we find the most uniform, the most extensive stratified deposits open to our observation. The physical and biological history of the continents is there chiefly recorded. In these widespread strata of bygone ages we may also trace the structures which have resulted from mountain growths, and study the mechanics of earth movements.

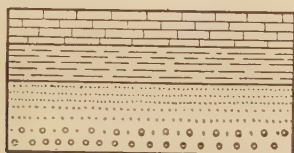
Strata of even greater extent, covering many thousands of square miles, lie beneath the oceans, but they are nowhere revealed to view.

Attitudes of Strata, Strike and Dip.—The attitude of a stratum is defined by the attitude of the bedding planes which limit it, and is described by the relation of the bedding plane to a horizontal plane. Thus, if the bedding planes of a group of strata extend in all directions horizontally, the attitude of the strata is horizontal. If the planes are inclined to the horizontal or if they are vertical, the attitude of the strata is inclined or vertical, as the case may be (Fig. 2).

Bedding planes are often seemingly parallel with one another over large areas, and the strata seem to maintain uniform thicknesses. Nevertheless, since banks of mud or sand are flat lenses, the thicknesses vary and the bedding planes approach or spread

apart. These variations become significant when we seek to drill to a buried coal bed or oil sand. It may then become essential that we determine how the strata to be penetrated change in thickness toward the drill hole, in order that we may tell how deep a hole we must drill to reach a certain bed. This, indeed, is a constant problem of the geologist engaged in drilling an oil field.

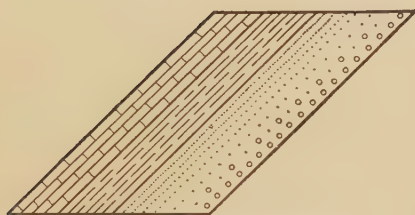
Where currents of wind or water have drifted dust and sand, the slope of the drift may be as steep as the dust or sand will lie—



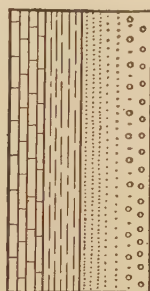
Horizontal strata of limestone.

Horizontal strata of shale.

Horizontal strata of sandstone and conglomerate.



Inclined strata of limestone, shale and sandstone.



Vertical strata of limestone, shale and sandstone.

FIG. 2.—Diagrams illustrating the positions of horizontal, inclined, and vertical strata.

as steep as one vertical to two horizontal. The slope is a bedding plane of the gathering drift—the front of it at one time, a bedding plane in it when covered by additional strata. Such bedding planes are evidently inclined when they form, and the strata between them are equally inclined. They are the foreset beds of a delta, gathered on its advancing front; or the shifting layers of a sand dune, blown over its top; or the deposits lodged on the face of a desert terrace, washed down its surface by a cloudburst.

Inclined strata, so formed, are always small lenses, with but little extent upward or downward. Below, they end against the

surface or stratum over which they are built out. Above, they are cut off by the wind or water that transports their material. The next stratum covers their edges. This arrangement is called *cross-stratification*.

Cross-stratification is an original structure due to conditions of deposition by wind or water. It does not demand attention as an element of geologic structures, except where the thickness of cross-stratified beds is to be measured. It then presents special problems, sometimes on a large scale.

Strata which were originally laid down flat, or nearly so, and which extended parallel with one another under the sea bottom or under wide plains, assume an inclined attitude, as they subside into the earth or as they are lifted in plateaus and mountains. They then appear as parts of large geologic structures. Their once orderly relations of parallelism with one another are disturbed. Their new relations suggest how they have been disturbed. It is, therefore, the task of the geologist to ascertain both sets of relations, the original order in which the strata were formed, and the disturbed arrangement in which they lie.

To describe these relations he employs certain arbitrary references, particularly what are called *strike* and *dip*.

If a stratum be inclined, the largest angle of inclination between the bedding plane and the horizontal plane gives the measure of the inclination. It is called the *dip angle* or the *dip*. If we assume a horizontal plane, $ABCD$, which cuts a bedding plane, $WXYZ$, the acute angle between the planes, measured in a plane vertical to their common trace, is the dip angle (Fig. 3). Let it be noted that the dip angle must be measured in a plane at right angles to the trace, MN . That is the largest of all the angles which might be measured between the bedding plane and the horizontal.

The trace MN of the horizontal plane with the bedding plane is a datum line by which the direction of the extension of the stratum may be defined; for if one follows MN one must follow the surface of the stratum in which MN lies. MN is a horizontal line; any horizontal line makes an angle with the north-south meridian and this angle is the *bearing* of the line. When the horizontal line lies in the surface of the stratum, as MN does, it gives the bearing of the stratum, and this bearing is called the *strike*.

From the preceding we deduce the definitions of strike and dip as applied to strata:

(a) The *strike* of a stratum is the bearing of a horizontal trace on the bedding plain.

(b) The *dip* of a stratum is the angle between a bedding plane and the horizontal, measured in a plane at right angles to the strike.

It is evident that a horizontal stratum strikes in all directions. A vertical stratum has a dip of 90 degrees. Strike and dip, being angles, are expressed in degrees. Strike is commonly stated

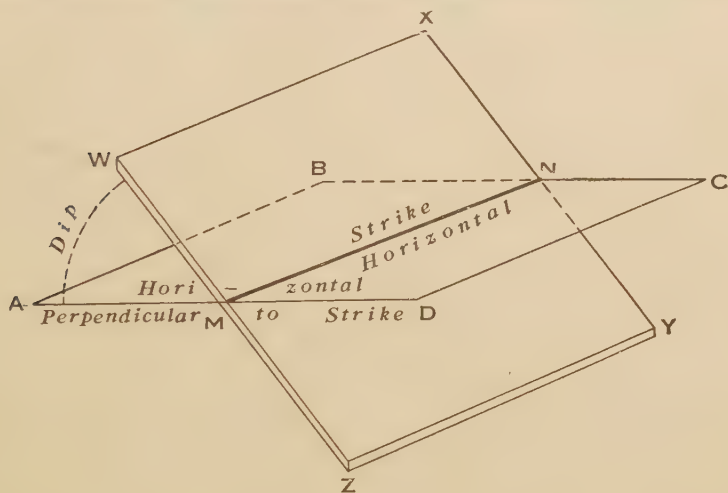


FIG 3.—Strike and dip.

as so many degrees east or west of north, thus: strike N. 30 E. The amount of dip is given by its angle, as for instance, 50 degrees, but there are always two planes which may dip at a given angle from any given strike. Thus, if the strike be northeast the dip may be northwest or southeast. Therefore the direction of dip also must be stated.

The full statement of the position of a stratum accordingly takes the following form: strike N. 30 E., dip 50 SE.; or, since the direction of dip is at right angles to the strike, the position may be defined by writing: dip 50 S. 60 E., with equal accuracy and greater brevity.

CHAPTER II

MECHANICAL DISTURBANCES OF STRATA

Forces Involved.—The forces which produce and change the forms of strata are internal attractions, chemical reactions, gravity, tangential pressures, and vertical uplifts. With the exception of tangential pressures and uplifts these forces act upon strata during the period of accumulation and consolidation, as well as later, and their effects during the formative stage of the rocks influence the later deformation. We may thus distinguish original or formative structures from those which are due to later disturbances.

Original Structures.—Original or formative structures are those which develop during the accumulation of the stratum or of a continuous series of strata. In stratified rocks stratification is the major original structure.

Consolidation of mechanical sediments is an important part of the process of forming strata. The effective force is gravity, which acts to press the particles closer together and to bring them into contact. The interstitial air or water is pressed out in proportion to the effect of compacting. It is clear that the possible effect of consolidation in reducing volume must depend on the proportion of pore space to grain space, and also, since the consolidation is an effect of settling under weight, it will result in a proportionate decrease in thickness of strata.

Assuming the least compact state of solid strata to be that in which the grains touch one another, it has been shown by Slichter theoretically that the pore space in sands of uniform spherical grain may range from 47.64 per cent down to 25.95 per cent, according to the arrangement of the grains.¹ If the grains be angular the pore space may be even greater in proportion to

¹ SLICHTER, C. S., Theoretical Investigation of the Motion of Ground Water. U. S. Geol. Surv., *Ann. Rept.* XIX, Pt. II, pp. 306-317, 1899.

the whole, but where the grains are of mixed sizes it may be less than the minimum for spherical grains. Wind laid sediments are apt to be looser and more uniform in size than water laid sediments, and the effect of compacting under load is then greater. In any case, however, an effect of vertical pressure due to loading must be to reduce the thickness of strata by consolidation by a notable amount. According to the range indicated by Slichter, the reduction in thickness may readily be as much as one-fifth.¹

Since the thinning of the stratum by consolidation is a considerable fraction of the vertical thickness, it follows that the absolute amount of thinning will be greater for thick beds or in the thicker part of a variable bed. The subsidence of the upper surface of any stratum or of a group of strata will vary accordingly, and so also the departure of that surface from the original, nearly flat conditions. Thus, the settling of the materials may be one cause for the development of gentle flexures in a series of strata.

Consolidation also increases the strength of strata in an important degree. As is pointed out by Van Hise, strength depends upon the number of points in contact and consolidation increases that number, as well as the bonds of adhesion and cohesion among the grains of sediment.²

Cementation, the process of cementing sediments by deposition of substances brought in solution, strengthens rock by knitting the particles together in a matrix. Lime, silica, and iron oxide are the more common cements. The effect depends upon the percolation of solutions, and is therefore common in strata of large grain and large pores, such as sandstones, whereas it is practically lacking in fine-grained rocks like shales. Strata are thereby rendered less flexible, more rigid, and therefore more competent to resist when subject to pressure in the direction of the bedding.

Limestone, in view of the ease with which calcite recrystallizes, is self-cementing and is among the strongest of sedimentary rocks.³ It therefore forms the controlling competent strata in a series in

¹ For observations of the pore space of many sands, soils, and artificial substances, see KING, F. H., *Principles and Conditions of Movements of Ground Water*. U. S. Geol. Surv., *Ann. Rept.* XIX, pp. 209-216, 1899.

² VAN HISE, C. R., *Treatise on Metamorphism*. U. S. Geol. Surv., *Mon.* XLVII, p. 596, 1904.

³ ADAMS, F. D., On the Amount of Internal Friction Developed in Rocks during Deformation, and on the Relative Plasticity of Different Types of Rocks. *Jour.* vol. XXV, pp. 626-627, 1917.

which it is interbedded with sandstones and shales and which transmits pressure in the direction of the bedding.¹

FLEXURES AND FOLDS

General Statement.—The original position of strata is flat, as a rule, since it corresponds with the bottom of the basin in which they are laid down. An extensive coal bed is an example of extreme flatness corresponding with the level at which the vegetation grew. Deposits of mud or sand may accumulate on gently sloping bottoms, but the slopes are very gentle, usually less than two or three degrees from the horizontal. In spite of this originally flat and nearly horizontal attitude we find beds of coal or mud rock or sandstone or limestone bent and tilted. In the warping of the earth's surface they have sunk down or been raised up, and have thus been flexed from their original position. If subsequently compressed horizontally, they become more or less sharply folded up and down. Series of strata, often of very great thickness, thus come to lie in the form of basins and domes, troughs and arches, or closely compressed contortions. They have been flexed and folded after they were deposited.

Sir James Hall, a Scotch geologist, as far back as 1788 correctly observed and interpreted the convolutions of strata, and in 1812 he wrote as follows regarding his observations of the attitude of the rocks in the cliffs of the coast of Berwickshire, Scotland (Frontispiece):

I reckoned sixteen distinct bendings in the course of about six miles, each of the largest size and reaching from top to bottom of the cliffs, their curvature being alternately concave and convex upwards. . . . These strata seem to have been originally deposited in a position nearly horizontal, and many of the particular beds possess that peculiar undulation on their surface which we meet with on a sandy beach, when the tide has left it, and which affords the most unequivocal indication of aqueous deposition. There is reason to believe also that the strata constituting these convolutions, though now detached from each other, have at one period lain in continuity and horizontally; that by the exertion of some powerful mechanical force they have been compelled to assume their present contorted shape; that their continuity still exists below, and would be seen, could we penetrate into the masses under the

¹ Adams, F. D. On the Amount of Internal Friction in Rocks. *Jour. Geol.*, vol. XXV, pp. 626-627, 1917..

level of the sea; the interruption of their continuity upwards having arisen from a removal of part of the rock, by some of those revolutions which have everywhere agitated and corroded the surface of our globe.

In the year 1788 it occurred to me that this peculiar conformation might be accounted for by supposing that these strata, originally lying flat and in positions as nearly level as might be expected to result from the deposition of loose sand at the bottom of the sea, had been urged when in a soft, but tough and ductile state, by a powerful force acting horizontally; that this force had been opposed by an insurmountable resistance upon the opposite side of the beds,—or that the same effect had been produced by two forces acting in opposite directions; at the same time that the whole was held down by a superincumbent weight, which, however, was capable of being heaved up by a sufficiently powerful exertion.¹

Sir James then described certain experiments which he made to test his theory by compressing layers of cloth horizontally under heavy weights. By this means he obtained folds sufficiently like those he had observed in the rocky strata to satisfy him that the process had been correctly interpreted. Anyone can make a similar observation by wrinkling a tablecloth or observing the character of the folds in his coat sleeve, but the folds in the cloth must be magnified from inches to tens of miles to equal those of the folded mountain ranges of the earth's crust.

In the century and a quarter which has elapsed since Sir James was the first to recognize the true character of rock folds, the study of their forms and of the mechanical conditions that control their development has become a technical branch of geology, and he would be puzzled, no doubt, to read current descriptions couched in terms that have become necessary to designate different kinds of folds or parts of them. In coal mining, in the development of oil fields, in metal mining, and in theoretical geology the discrimination of different types is essential to an adequate understanding of the structures and of the various valuable deposits sometimes connected with them.

Folds which are "alternately concave and convex upward" lie in alternation in any continuous, wrinkled layer, whether it be of cloth or of rock. Those which are convex upward rise as it were from the surface of those that are concave upward, and at

¹ HALL, SIR JAMES, Bart., On the Vertical Position and Convolutions of Certain Strata and their Relation with Granite. *Trans. Roy. Soc., Edinburgh*, vol. VII, 1815.

their ends they fade out into the general flattish surface. A common form of wrinkles is that of a cigar sliced in half lengthwise. Folds are rarely isolated. They occur in groups. The strata are continuous beneath the surface of the ground, as Sir James inferred and as has been abundantly proved by mining operations. There would also be a continuous surface above ground, if erosion did not immediately attack any fold that begins to rise above a local or general base level and wear away the up-arched strata. This fact of former continuity should not be forgotten as we proceed to dissect the once continuous structures into their parts.

Up-arched folds, those which are convex upward, are known as *anticlines*. Depressed folds, those which are concave upward, are called *synclines*.

These terms came into use early in the investigation of the contortions of strata, when geologists began to distinguish the various forms of flexures or folds they observed in the mountain ranges. De la Beche thus defined an anticline:¹

Anticlinal line is that line from which the strata dip on either side: the ridge of a housetop will convey an idea of this line, the slope of the roof representing the dip of the strata.

Syncline signifies the reverse of an anticline, that is, a basin or canoe shape, and monocline designates strata which dip in one direction only. These definitions and others are given in detail in the following section.

Folds and Their Parts.—The two great types of folds are the syncline and the anticline.

The syncline is the simplest type (Fig. 4.) It is a depression of the strata from a flat to a basin-shaped form. In cross-section it may be shallow and gently rounded, or deep, straight sided, and sharply angular. Sometimes the sides are closely pinched together. In plan view a syncline may be oval or long, narrow, and acute at the ends. Geometrically a syncline is characterized by the fact that it is concave upward. Geologically it is determined by the presence of younger strata within the basins of the older.

The anticline or arch (Fig. 5) is the companion of the syncline. It is an elevation of the strata in a direction opposed to gravity, from a flat to a dome-like or half cigar-shaped form. The cross-section varies from a broad, gentle arch to an acute, straight-

¹ DE LA BECHE, H. T., "Geological Manual," p. 507, 1832.

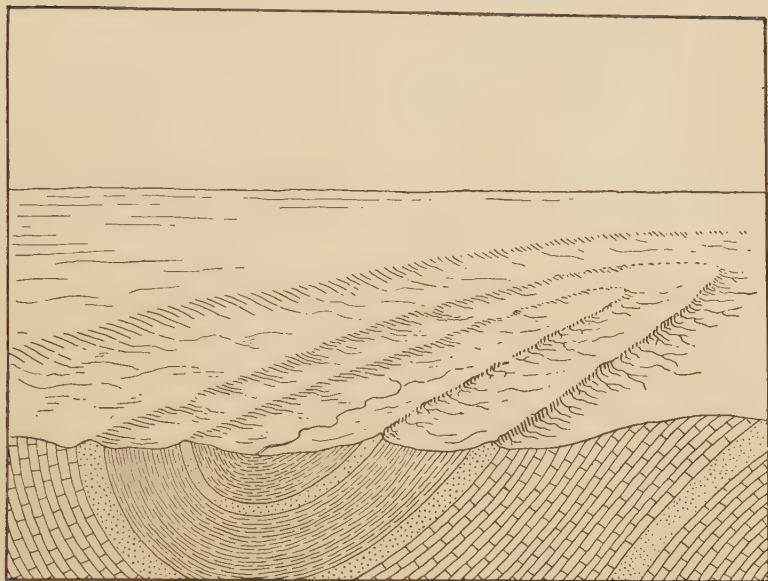


FIG. 4.—View of a syncline, showing the outcrop on the surface and a vertical cross-section.

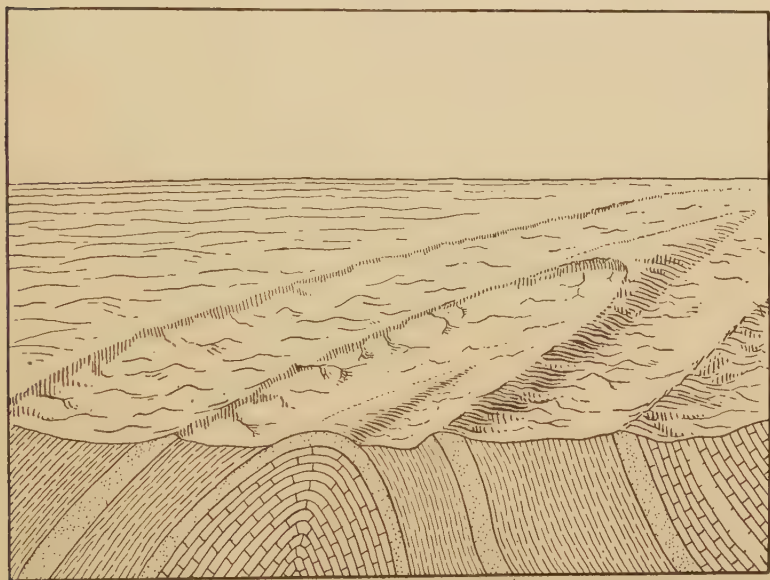


FIG. 5.—View of an anticline, showing the outcrop on the surface and a vertical cross-section.

sided roof. In plan anticlines are often long and narrow. Geometrically the anticline is distinguished by its upward, convex curve. Geologically it is recognized by the presence of older strata within the arches of the younger.

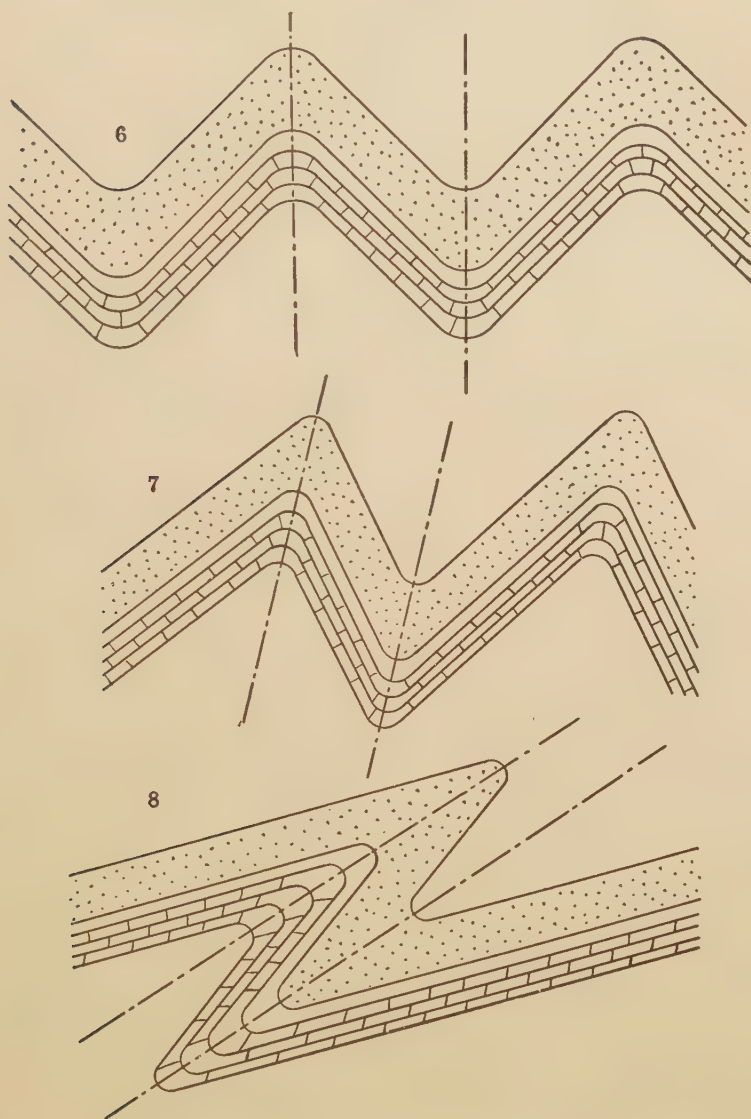
Any syncline or anticline consists of two sides, which meet along the line of lowest depression in the syncline or along that of greatest elevation in the anticline. The sides may be called the limbs, slopes, flanks, branches, legs, or shanks. It is customary to regard an anticline as extending from the synclinal axis on one side to the parallel synclinal axis on the other side. Also it is usual to include in any syncline all the structure between two anticlinal axes. Thus every anticline consists of two half synclines, and every syncline consists of two half anticlines. (See Figs. 6-8.)

In the last few lines we have referred to the axes of synclines and anticlines. The word axis is here used in the sense of a definite line of reference. In a syncline the axis is that line which connects the lowest points of the trough along any one stratum. In an anticline the axis is that line which connects the highest points of the arch along any one stratum. There is in every fold an axis for each and every stratum. Now if we think of the strata as infinitesimally thin, the axial lines will touch one another and will be the lines of the axial plane or surface.

The preceding statement may be put in another way, namely, the axial plane or surface of any fold is that plane which bisects the angle between the limbs of the fold.

By reference to Figs. 6, 7, and 8 it will be seen that if the strata dip equally on both sides of the fold the axial plane is vertical, but if the dip on one side of the fold is gentler than on the other the axial plane will be inclined in the direction of the gentler dip. This fact is sometimes of importance, as in drilling for oil, for instance, when the object may be to strike the axis of the fold at a depth of 3,000 or 4,000 feet.

In a preceding paragraph, page 9, we have defined the strike and dip of strata. We also speak of the strike of the axial plane of a fold or of the axis of a fold, meaning the bearing of a horizontal line drawn upon the axial plane. We may also speak of the dip of the axis, meaning the dip of the strata in the direction of the axis immediately on the crest of an anticline or in the bottom of a syncline; but it is better usage to substitute the word pitch



FIGS. 6, 7, and 8.—Diagrams of folds showing the positions assumed by the axial planes.

FIG. 6.—Upright symmetrical fold; the axial plane is vertical.

FIG. 7.—Unsymmetrical fold; the axial plane is inclined toward the gentler dip.

FIG. 8.—Overturned fold; the axial plane is inclined at a low angle.

for dip in speaking of the inclination of the axis, and thus to distinguish the pitch of the strata on the axis from the dip of the strata on the limbs of the fold.

It is important to recognize the relation which exists between the strike of strata and the axes of folds. Where folds are long and narrow the strike of the strata often runs parallel with the

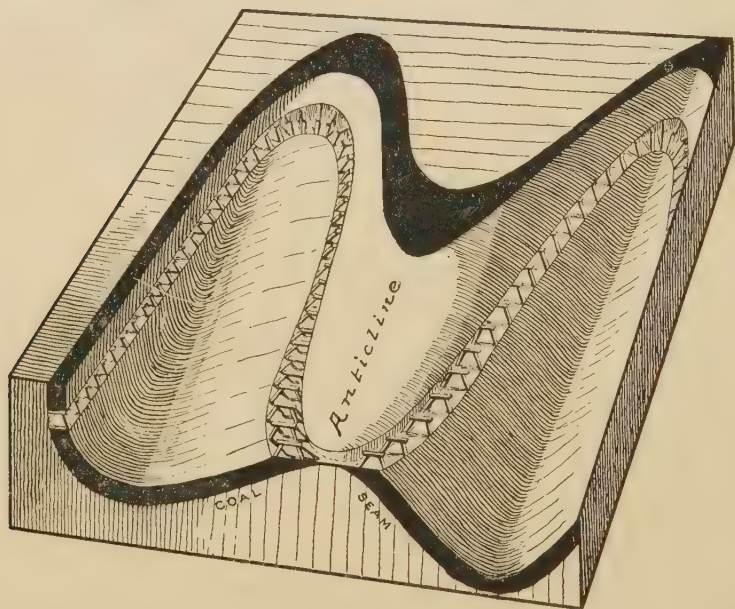


FIG. 9.—Course of a gangway on a coal bed which is folded over an anticline and in two synclines.

Note how the gangway, which being horizontal follows the strike of the coal, winds alternately around the anticlinal and synclinal axes.

Note also that the apparent width of the coal in the outcrop changes, from the true thickness where the bed is vertical (at the left) to a seemingly great width on the anticline and syncline, where the pitch is very gentle.

axes of the anticlines and synclines for long distances. In the Appalachians, for instance, this parallelism may extend for two or three hundred miles. But as the beds approach the axis their strike turns toward it and crosses the axis, being at right angles to the strike of the axis itself at the point of crossing. Strata thus loop backward and forward alternately around synclinal and anticlinal axes (Fig. 9).

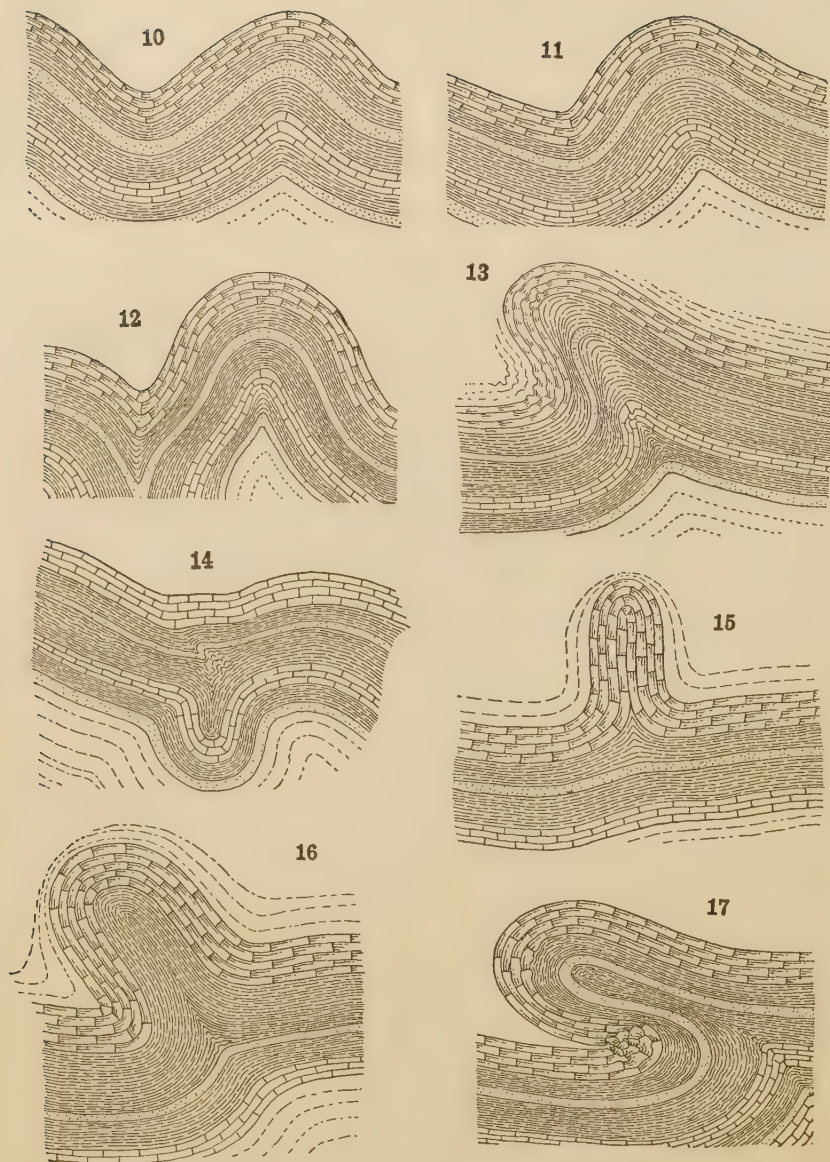
Classification of Folds.—Folds are classified in four different ways: (a) By the relative amount of the opposed dips of the limbs; (b) by the form of cross-section, involving the relative thicknesses of any stratum on the limbs as compared with the axial regions; (c) by the degree of compression; and (d) according to the combination of anticlines and synclines.

(a) If we compare the opposed dips of any anticline or syncline, it is evident that they may be equal or unequal. If equal, we have a *symmetrical* fold; if unequal, an *unsymmetrical* one (Figs. 10–13). The amount of the dip is not involved in this distinction. Thus, the dips of a symmetrical anticline may be very gentle or may be vertical, but they must both be the same. In an unsymmetrical fold one limb may lie nearly flat, the other stand vertical, at right angles to it. The actual difference of dip between the two limbs may go even farther, the steeper dip passing the vertical and becoming overturned. In this way, in an extreme case, the overturned limb may become practically parallel with the upright limb, and we then have a completely overturned fold. These various folds are illustrated in Figs. 13, 16, and 17, and the special names describing each kind are given with the illustration.

(b) When strata are bent into folds they may adopt *concentric* or *similar* curves, according to the mechanical conditions under which the folding occurs. When the strata bend *concentrically* they everywhere retain their individual thicknesses. The center of curvature remains constantly the same, but the radii of curvature increase from near the center outward. With the increase in radii the curves flatten. Thus concentric folds die out upward and downward (Fig. 18).

Similar folds embrace equal angles between the limbs of successive strata. The curvature of the limbs is often very slight, and they lie parallel to one another, like the sides of many V's set one inside the other. The curvature is apt to be concentrated in a short section, and is therefore more or less acute. The center of curvature for different strata is never the same. The distinguishing characteristic is that the strata are thinner on the limbs of the folds than they are between the crests of the anticlines or the bottoms of the synclines (Fig. 19).

(c) Folds may be classified as *open*, *closed*, or *squeezed*, according to the degree of compression they have suffered. An open fold is one which may be bent closer without disturbing the



FIGS. 10-17.—Types of folds.

- FIG. 10.—Symmetrical or upright fold, open.
 FIG. 11.—Unsymmetrical or inclined fold, open.
 FIG. 12.—Symmetrical or upright fold, closed.
 FIG. 13.—Unsymmetrical fold, closed and overturned.
 FIG. 14.—Syncline showing a keel; a carinate syncline.
 FIG. 15.—Carinate anticline, the lower strata remaining flat.
 FIG. 16.—Carinate anticline, overturned.
 FIG. 17.—Carinate anticline, recumbent; or recumbent fold.

parallelism of the strata on any limb (Figs. 10 and 11). A closed fold is one which cannot bend closer without distorting the bedding (Figs. 12-16). A squeezed fold is one in which the compression has gone so far as to alter materially the thickness and



FIG. 18.—Concentric folds.

form of the strata or to shear them off (Figs. 17, 20, 21, and 25-29).

(d) Anticlines or synclines seldom occur as separate individuals. They are usually connected, lying side by side in alternation, uniting by convergence of several axes to form one, or dying out

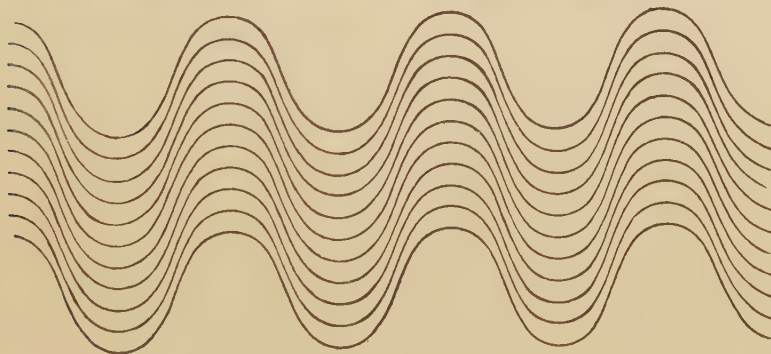


FIG. 19.—Similar folds.

by the merging of an axis with the slope of a stratum. Thus it often happens that many anticlines and synclines are related to one another as parts of a *composite structure*. Indeed even those folds which we regard as simple are usually found to be composite in detail. That is, there are minor folds involved in their limbs.

Composite folds may be small or large. The microscope reveals folds which are parts of macroscopic folds, and even sub-microscopic plications may occur in great detail. On the other

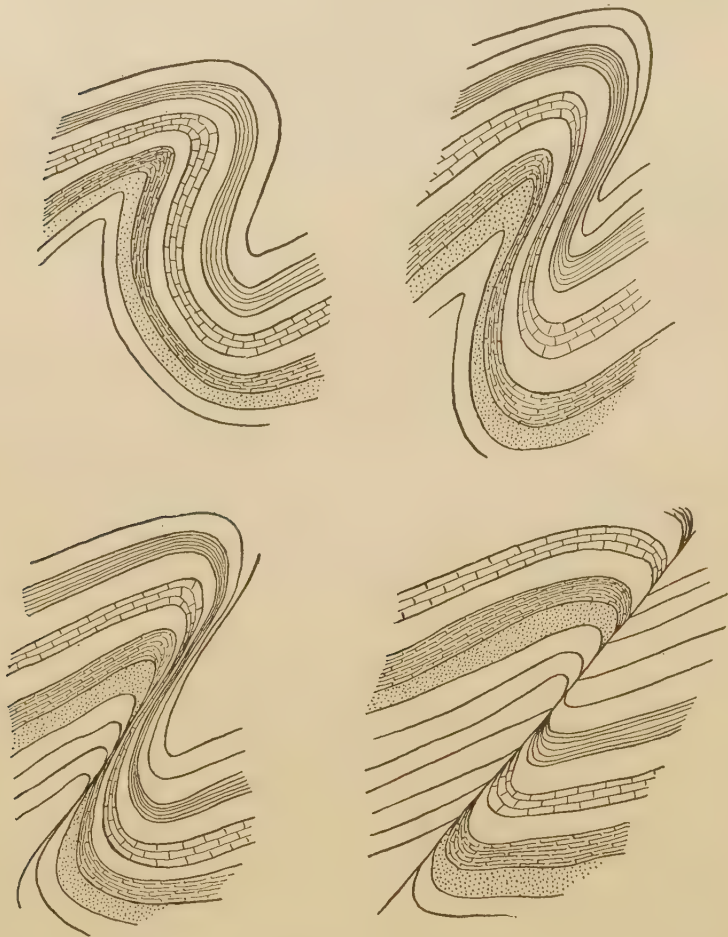


FIG. 20.—A recumbent overturned fold, passing into an overthrust.
(After Heim.)

hand, large simple folds, several miles across, are commonly parts of great composite structures which are nothing else than major folds. Thus size is not a condition of the idea of a composite structure.

It is convenient to have names by which to distinguish different composite structures. Dana gave the name *synclinorium* to composite synclines of large dimensions.¹ A mountain range

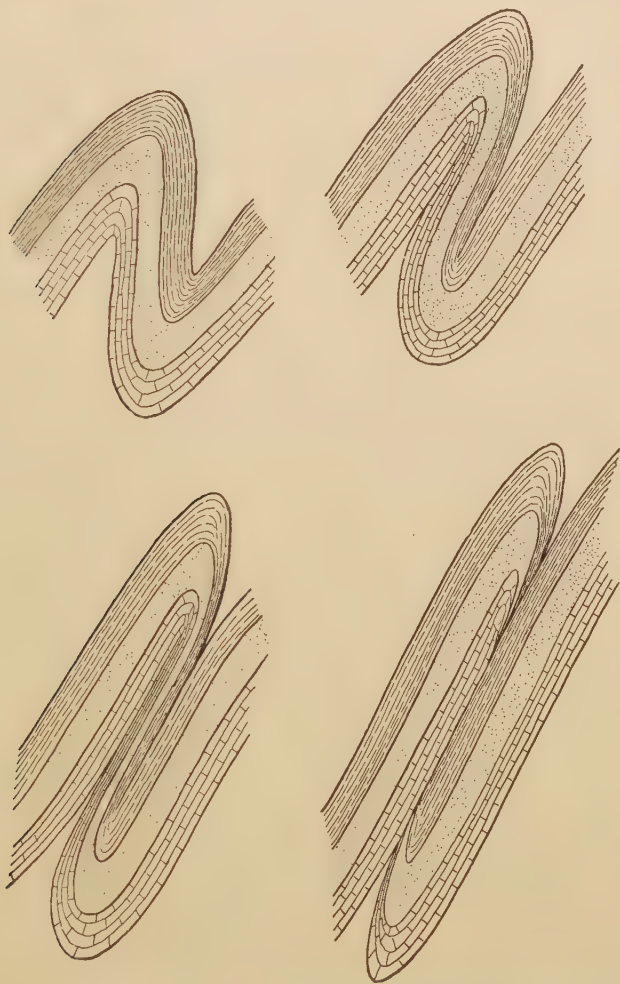
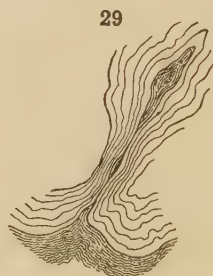
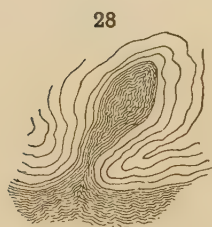
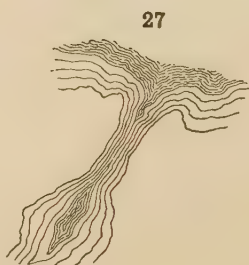
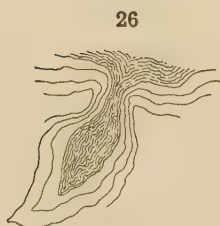
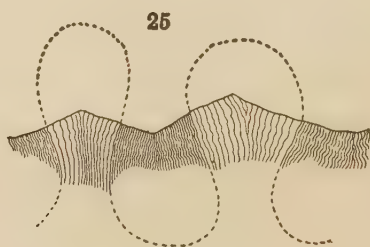
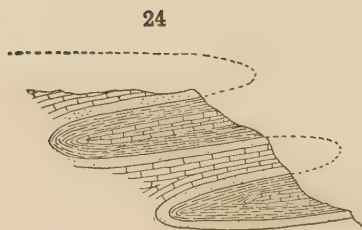
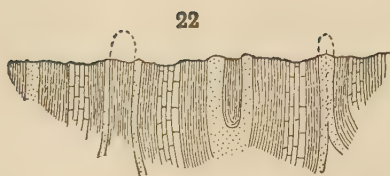


FIG. 21.—A recumbent fold with parallel limbs, passing into an overthrust.

which exhibits a synclinal folded structure is a *synclinorium*. Or, if it have an anticlinal structure composed of many anticlines and

¹DANA, J. D., "Manual of Geology," 4th ed., p. 380, 1895.



FIGS. 22 to 29.—Types of folds, continued.

FIG. 22.—Repeated carinate or "isoclinal" folds, upright.

FIG. 23.—Isoclinal folds, inclined.

FIG. 24.—Isoclinal folds, recumbent.

FIG. 25.—Fan structure, upright.

FIG. 26.—Squeezed syncline.

FIG. 27.—Squeezed syncline and detached core.

FIG. 28.—Squeezed anticline.

FIG. 29.—Squeezed anticline and detached core.

(After Heim and de Margerie.)

synclines, it is appropriately called an *anticlinorium*. In a synclinatorium the younger strata occupy the central position in the structure; in an anticlinorium it is the older rocks which are found there.



FIGS. 30-31.—Folds in "Rothidolomit," a hard dolomitic limestone of the Alps. (After Heim. *Mech. der Gebirgsbildung*, Plate XV, Figs. 7 and 8.)

The specimen consists of layers of dense yellow dolomite and greenish clay slate. The latter appears more minutely crumpled, the former arched without crumpling.

Fig. 31 is an enlargement of part of Fig. 30.

In the process of folding the layers of dolomite worked as competent strata and determined the form of the folds. The slaty layers were incompetent and adjusted themselves to the interspaces.

The terms *geosyncline* and *geanticline* are used to describe very large depressions or very large elevations of the earth's surface. Their use does not, however, imply that the rocks in the geosyn-

cline or within the geanticline are folded. They may not even be stratified. Within a geanticline they may be massive rock, like granite, which cannot fold because it is not bedded. Or in a geosyncline they may be modern, flat-lying sediments, as in the

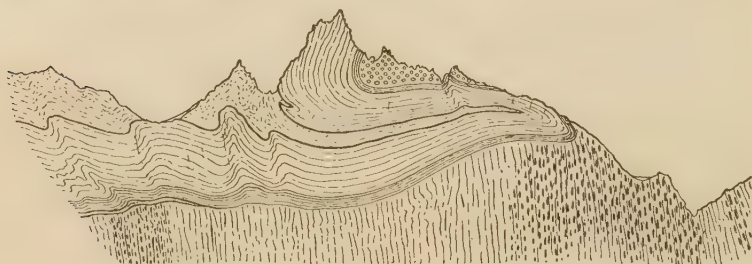


FIG. 32.—Overturned fold in the Alps. (After Heim.)

Valley of California. Thus “syncline” and “anticline” have lost their original meaning in this connection and merely indicate a trough or uplift, as the case may be.

Note.—The facts by which the occurrence of folds may be recognized in nature are discussed in the chapter on Field Methods.

CHAPTER III

JOINTS

Description.—Joints are planes on which rocks part with a smooth surface and more readily than through the mass. Thus defined, joints might be confused with smooth bedding planes, but there is a distinction. Bedding planes are original; they formed as the beds accumulated. Joints are not original; they are developed by strains that change the rock mass after it has taken shape.

Joints occur usually in numbers, often in sets, those which constitute a set being roughly parallel with one another. Two sets may occur, intersecting each other approximately at right angles and dividing the rock into slabs; or there may be a third set, running roughly at right angles to the other two and cutting the mass into blocks. Such blocks are rectangular or rhomboidal.

In very firm rock, joints may be so tightly closed that they are invisible to the eye and part only when struck a sharp blow. They are then called close or blind joints, and it is as such that they develop in rocks beneath the surface. When, however, rock masses are moved, joints may become planes of slipping or, nearer the surface, may open, producing open fissures. Exposed at the surface, joints are planes of weakness along which chemical reaction, solution, and deposition of insoluble minerals occur, so that joint planes may be brought out by the discoloration or unequal weathering along them.

Joints may be straight or gently curved. They may be short, be offset and continue, or branch and die out abruptly. They may, as stated, occur in parallel sets or may intersect at acute angles.

They may occur in any kind of rock—in sedimentary strata, in lavas, in massive igneous rocks, and in schists, but they do not have the same characteristics in all cases. The joints peculiar to each rock type are described in that connection. Here we take up particularly the jointing of sedimentary rocks.

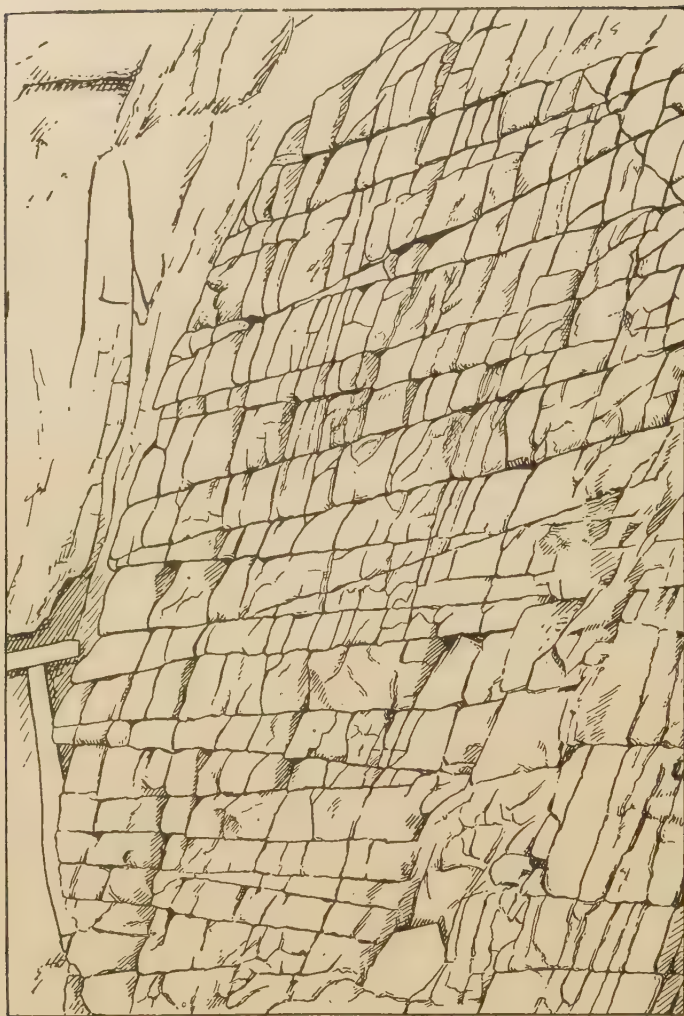


FIG. 33.—Joints in Greywacke, Currarie Port, South Ayrshire, Scotland. (Drawn from photograph in "Structural and Field Geology." By James Geikie, Plate XXXIV.)

Note the arrangement of the joints in two systems, the one from left to right, more strongly developed, the other up and down, less persistent. Minor diagonal joints are locally developed.

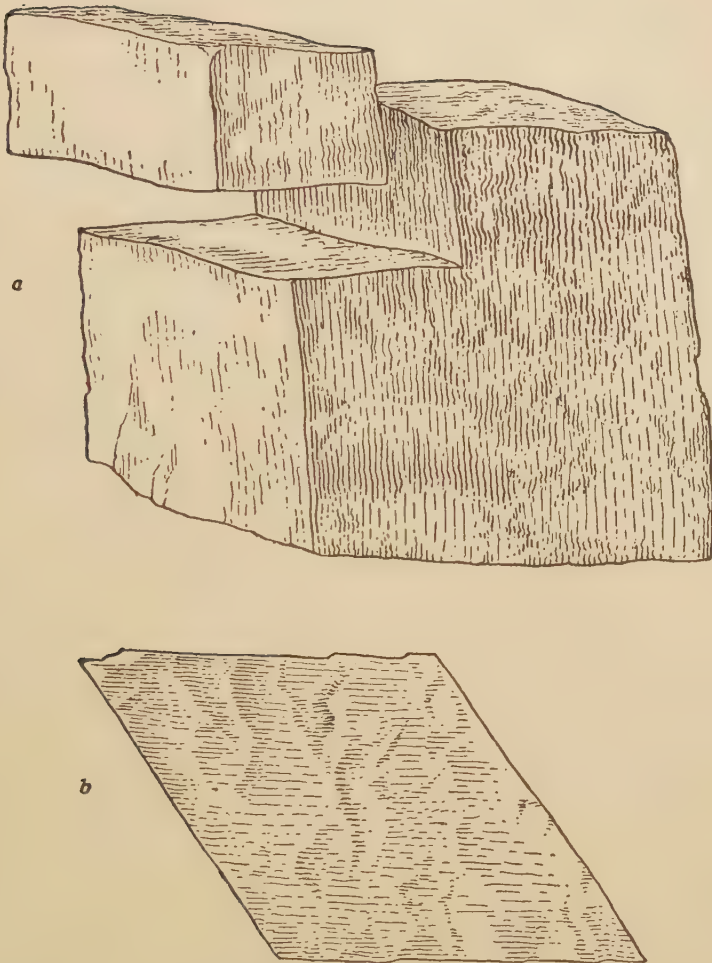


FIG. 34.—Drawing of specimen of jointed slate. (Natural size).

(a) Perspective view of block showing a piece detached on the parallel planes that traverse it according to the three systems of joints produced by pressure. Stratification does not affect either set of joints, the rock being homogeneous.

(b) Plan view of the joint block showing the great distortion of the ideal cube and the development of a rhomb by shearing along the joints.

Mud does not exhibit jointing, nor does shale, as a rule. When, however, shale has become slaty it commonly is jointed along planes which cut the slate with a remarkably clean, flat surface. The homogeneity of the material promotes the perfection of the structure, as soon as the rock is rigid enough to develop the plane. Limestone is both hard and homogeneous, and it is usually distinctly jointed. Sandstone is rigid, but lacks uniformity of grain and, though very generally jointed, it is more roughly blocked out. Conglomerate is jointed only when it has been subjected to such pressure that the matrix and pebbles were held together as a homogeneous mass. The joints then cut through matrix and pebbles alike with a smooth, clean break.

Joints in slate are sometimes accompanied by a discoloration, a gray or yellowish line, but a narrow one, because the moisture to which the alteration is due does not penetrate far from the plane. Carbonaceous material may be leached out or iron may be oxidized and hydrated, but there is no decomposition of the clay rock itself in such superficial changes.

Limestone is commonly dissolved along a joint plane, because the crystals of calcite are strained there and they yield more readily than they do in the mass. If the limestone strata are thick and extensive and the activity of solution is continued, caverns may result and the apparent labyrinth is developed according to the joint system.

Joints in sandstone are very commonly bordered by a deposit of iron oxide, more or less hydrated and consequently ranging from yellow to brown in color. They are conspicuous and when parallel are easily mistaken for bedding planes, especially in massive sandstone, where such planes are obscure. The criteria by which they may be distinguished are described in the section on practical problems, pp. 233-234.

Since jointing is a secondary development of structure and in sedimentary rocks is the effect of local or general, compressive or tensile strains, it owes its character to the nature of the major structures with which it is associated. The mechanical conditions of the development of joints belong, therefore, to the subject of mechanics of structure, and are discussed under that head, page 144.

Note.—For discussion and experiments on Joints, see PEARL SHELDON, Some Observations and Experiments on Joint Planes, *Jour. Geol.* vol. XX, pp. 53-79 and 164-183, 1912.

CHAPTER IV

STRUCTURES OF IGNEOUS ROCKS

General Description.—The structures of igneous rocks fall into two classes, those which are indigenous to the rock masses and those which are imposed upon the masses by their environment. Since both of these types of structure are imposed upon the rocks as they form, they are both original structures. In addition, igneous rocks may be sheared, faulted, and when bedded folded. They may thus have secondary structures imposed upon them. Like sedimentary rocks they may also be metamorphosed.

By indigenous structures are meant those which the rock mass assumes in cooling from the molten state. Here we must include that negative structure, *massiveness*, which is assumed by the larger masses. The fact that a massive rock cannot fold and can yield to distortion only by shearing obliges us to recognize massiveness as a structure which has important implications.

Jointing is a structure imposed in cooling and, unlike the joints produced by pressure, is a result of tension. We may imagine in a molten mass a number of centers of attraction toward each of which the cooling, and consequently shrinking, material is drawn. Between each two adjacent centers there will be a surface at which the attractions will be equal, but in opposite directions, and the rock will tend to part or may part, forming a joint. The distances between centers are usually measurable in inches or feet, that is, they are small in comparison with the magnitude of the masses. Hence in a large mass there are many centers. In a state of equilibrium as to attractions and pressures there would be a tendency for the centers to arrange themselves at equal distances and for each center to form around it a spherical body, consisting of the rock that had been attracted to it in the shrinking. But tangent spheres do not fill a space and the rock not included in them must be included in the resulting form. The latter is therefore a body of polygonal form, especially in horizontal cross-section. If condi-

tions were equal in all horizontal directions it would be a hexagon, but they rarely are and pentagons or quadrilaterals are common. The block does not assume the polygonal form in vertical cross-section, because of the influence of the cooling surface and of gravity. Shrinkage takes place toward the cooling surface and the blocks are pulled downward by their weight. These two forces divide the cooling mass along planes perpendicular to their resultant, which is usually nearly vertical. The partings are therefore approximately horizontal. The effect of these several partings is to divide the mass into polygonal columns, which commonly assume a more or less nearly vertical position, but may be inclined or curved, according to the position of the cooling surface.

Bedding is a structure assumed by lavas, either as a result of successive flows or as an effect of cooling. It is irregular, since the surfaces produced by either condition of its development are uneven. The blocks of adjacent lava beds interlock in moving past one another when the beds are bent and consequently do not give rise to the smooth curves that are characteristic of flexible sedimentary strata.

Of the indigenous structures of igneous rocks, massiveness is typical of large masses which cool deep beneath the surface. Jointing is common to both classes, those that cool in the depths and those that cool on the surface, but there is the difference that the joints in the former are compression joints, due to external pressures, whereas those in the latter are shrinkage joints produced during cooling and consolidation. Bedding is characteristically developed in lavas, but it also occurs in granite, as a kind of horizontal parting on a very large scale. The conditions which give rise to its formation in the latter case are obscure.

The imposed, original structures exhibited by igneous rocks are those shapes which they assume when intruded among other masses. They then fill spaces, which either were open or which they force open, and they take the form of the space.

These forms have received distinctive names: *batholith*, *laccolith*, *stock*, *sill*, *dike*, and *offshoot*.

A batholith is a large mass, commonly of granite, which is intruded from greater depths into rocks some thousands of feet below the surface, but which does not reach the surface. The mass is usually very large. It may comprise many thousand cubic miles of rock, all of which was apparently molten at one and the same

time and cooled during the same geologic epoch. It does not necessarily follow that it was all melted at once, or in a single mass. It may represent the product of prolonged melting and of the gathering of an infinite number of relatively small streams of liquid granite. The forms of batholiths are not known, but their upper surfaces tend toward a rounded shape and their sides follow great irregular structural surfaces, presumably faults, along the trends of mountain ranges.

A laccolith is a mass of rock which in rising, molten, from below forces itself in between strata and raises those that are above it in a dome. Cracks are formed in the roof and are occupied by dikes or offshoots from the larger mass. The bottom of a laccolith is flat, conforming to the underlying bed. The top is arched like the overlying strata. The plan may be rounded or oval or a half oval, depending on the conditions of intrusion.

A stock is an irregular body of intrusive rock which has an indefinite vertical dimension, rising as it does from below, but is relatively small in horizontal diameters. It occupies a group of fissures in the country rock, presenting a central column of irregular form with many branches. The rock of a stock has cooled beneath the surface and has been exposed by denudation. A similar form of more superficial development and one which may represent the upper part of a stock is the volcanic neck, the material which cools in the throat of a volcano.

A sill is a sheet of intrusive rock intruded between sedimentary strata in such a manner that it extends parallel with them and appears to constitute a member of the conformable stratified series. Its thickness is commonly a few feet or tens of feet, while its area may be several square miles. The sill and the laccolith are related forms, both being intruded between sedimentary beds and the difference in shape being determined by the relative ease with which the strata arched up to form a laccolith or split apart over a large area to give space for a sill.

Dikes and offshoots from dikes or other molten masses occupy fissures, generally more or less nearly vertical, and consequently are wall-like forms. They are thin in horizontal width, long in the other horizontal dimension, and of indefinite depth. They often occur in great numbers, occupying a notable proportion of the horizontal dimension of a mountain mass. They thus correspond to and are characteristically developed in domes, such as the arched

strata above a laccolith or the greater volcanic uplifts of complex structure. Dikes may develop at great depths by the intrusion of molten rock along planes of strain, where they force the rock apart, or more superficially in cracks already parted. Offshoots are dikes which branch from larger dikes or other masses and which die out in moderate distances. Sometimes they spread out into irregular bodies at their ends.

The structures of igneous rocks are determined by the spaces into which the bodies of magma are intruded and by the conditions of pressure in the surrounding masses. Intrusions into sedimentary strata are of necessity superficial phenomena. Intrusions of igneous rocks into igneous rocks or into metamorphic forms of such rocks are deep-seated phenomena and are characteristic of the deepest zones exposed to our view by uplift and erosion. They therefore constitute the structures presented by the pre-Cambrian terranes and by other regions of very great, deep-seated intrusions, such as are found in the cordilleras that surround the Pacific. They do not, however, enter into the structures of sedimentary rocks, except as incidental and accidental occurrences.

CHAPTER V

FAULTS

General Description.—When a miner says that he has “struck a fault,” he means that the vein which he has been following has come to an end. Ordinarily it is cut off by a break or fissure and the dissevered part has been moved to one or the other side. A common situation is illustrated in Fig. 37. A *fault* thus implies

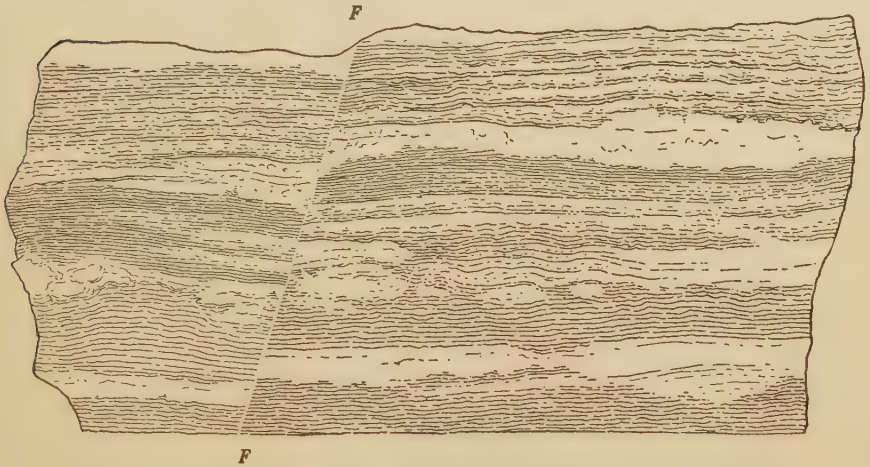


FIG. 35.—A fault in bedded rock. *FF* is the line of the fault, where the fault plane cuts the surface of the rock.

Drawn from specimen of bedded volcanic rock from near Lake Tahoe, Sierra Nevada, California.

a break and a displacement of the two parts with reference to one another.

Rocks are broken apart in various ways in the movements of the earth's crust, and not all breaks result in faults. There is about a fault an implication or order which is lacking in a disorderly break. Figure 36, for example, illustrates a broken mass in which the fragments are bounded by irregular fractures and lie in confused relations to one another. It is not possible

to restore them to their original positions with reference to one another nor to infer the action of the forces which crushed and scattered them. A fault usually exhibits a degree of orderliness which makes it possible to infer the nature of the movement of the separated parts with reference to one another and the direction

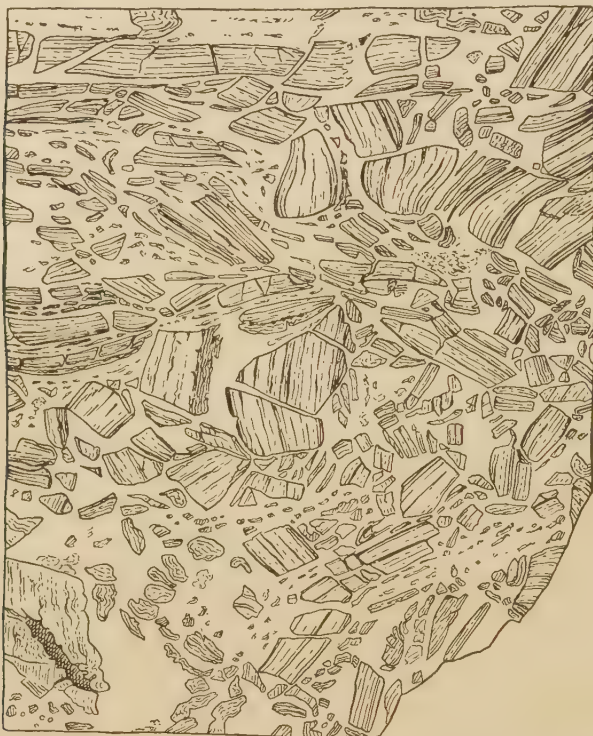


FIG. 36.—Brecciated Jaspilite from the Marquette iron region in Michigan
(After Van Hise.)

of the force which displaced them, provided we know certain elements of the problem.

A fault thus comprises two features: *a surface along which a rock mass has parted, and a displacement along that surface.* The miner finds that his vein has ended against an underground cliff and the continuation of it has been shifted up or down, to the right or left, or in some diagonal direction. His problem is to find out in which direction the continuation of the vein beyond the

fault has gone. A mistaken solution often involves heavy expense and possibly the loss of the mine, besides loss of reputation. A fault is thus a personal matter for mine operators as well as for capitalists.

The existence of a fault is recognized in geologic surveying as in mining by the fact that a stratum or group of strata or a vein, which should extend further, is cut off abruptly. That portion

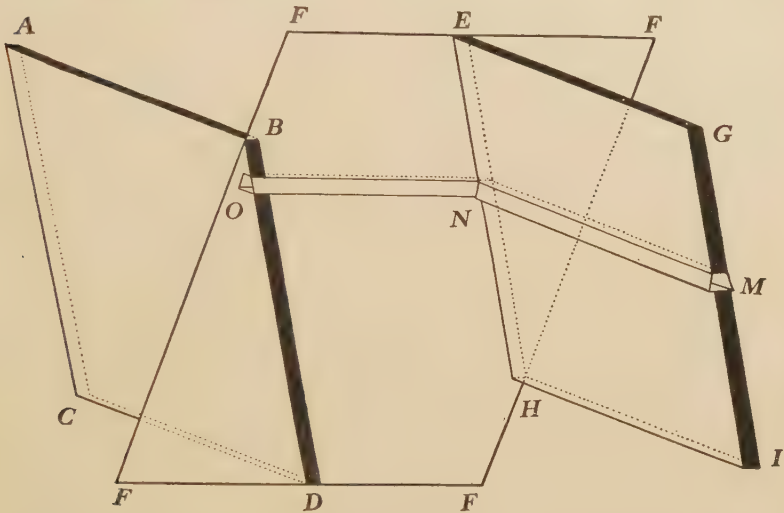


FIG. 37.—Perspective diagram showing a vein which is crossed and thrown to the left by a fault plane. The miner, having driven a gangway on the vein to the fault, recovers the vein by driving a cross-cut tunnel along the fault plane.

FF is the fault plane.

EGIH and *ABCD* are the sections of the vein.

MN is the gangway.

NO is the cross-cut tunnel.

If the miner had turned to the right, instead of to the left, at *N*, he would not have found the vein.

which we have followed ends at the fault plane. The continuation extends beyond the fault plane, but the stratum or vein is offset. Theoretically the offset may be in any direction whatever. The offset may be directly up or down, or diagonally up or down, or horizontal. There is offhand no reason to assume an offset in one direction rather than in another. A careful examination

of the fault plane may, however, disclose markings by which the direction of movement can be ascertained, and there are certain rules, based on mathematical relations, which serve to solve the problem correctly, provided always the initial assumptions are themselves correct. We shall see that there are several kinds of faults, and a particular rule does not give the correct solution of a fault problem unless it is applied to the right kind of fault. This should be too obvious to require statement, but the misapplication of rules has cost many hundreds of thousands of dollars in mining, nevertheless.

Faults may develop as irregular fractures or as smooth shearing planes. The former are typical of movements in the rocks near the surface, where the load does not hold the masses tightly together; the latter are produced only where the superincumbent load is so great that the parting cannot diverge from a smooth, flat, or curved surface, cannot become a zigzag break. This, of course, is the case at greater depths.

When displacement occurs on a zigzag break, open fissures result and alternate with closed sections along the fault. The reason is obvious when we examine the effects of movement, as they are illustrated in Figs. 38, *a*, *b*, and *c*. It is evident that the projecting shoulders must be pressed together and that the retreating surfaces must separate as they move past one another.

The effects of pinching and opening along fissures is of great importance in relation to ore deposits, for ore bodies occupy spaces, which may have been openings or may have opened as the ore deposit formed. Any one opening is limited by adjacent closed sections of the fissure, but others are apt to occur along its course, provided the mechanical conditions have been appropriately extended. Exceptions to this general condition are found, even in superficial ore deposits, if the ore has replaced the rock by chemical reaction. Then it may occur that the crushed section has been the seat of the reaction and the opened spaces may contain barren vein formations.

Open spaces along faults are often filled with broken rock, the crushed material produced in the movement under a pressure sufficient to break up the rock into fragments, but not so great as to reduce it to powder. Where the latter is the case the ground-up material forms a clayey mud, that is distributed somewhat evenly along the fissure. A mass of broken fragments along a

fault is called a *fault breccia*, while the corresponding crushed substance is known as a *fault gouge*. Both breccia and gouge are significant as evidences of the degree of pressure which has been exerted, and either one may give information as to the direction of displacement on the fault.

Under the great pressures which exist beneath deep rock masses, that is to say three miles or more below the surface, large empty openings cannot exist because the walls will not

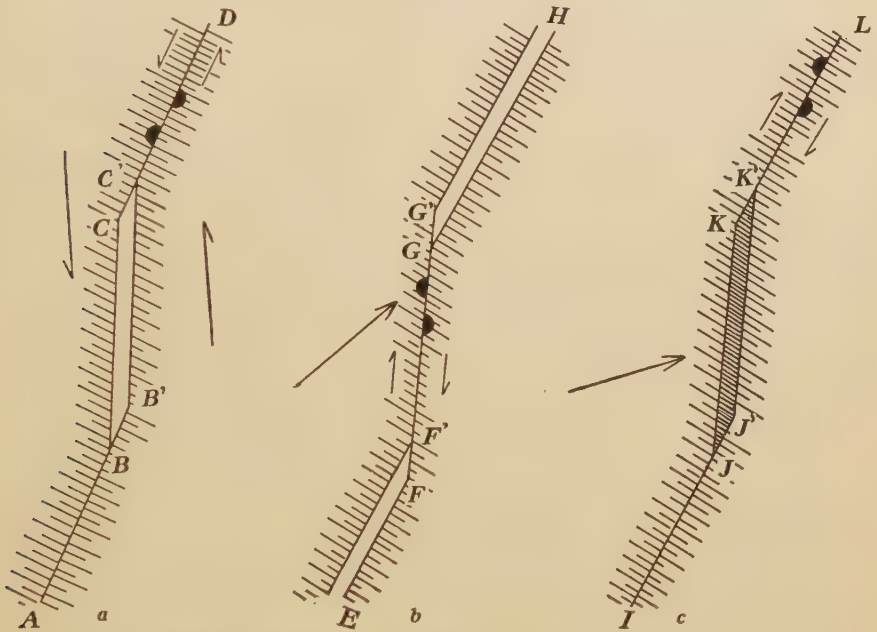


FIG. 38.—Diagrams showing the effects of movements on zig-zag faults, producing openings and crushed sections.

support the weight. Only small ones can remain open beyond the depth at which larger ones close, and this comparative statement can be carried down to where the largest possible empty openings are microscopic, or to where the sub-microscopic openings even are closed and we may say that there can be no openings at all. Following this line of reasoning we must recognize that open fissures and fault breccias are superficial in their occurrence. Even though they extend in hard, strong rocks as deep as we can mine, they must be closed at what is, geologically speaking, a

shallow depth. Faults are not thus limited to shallow depths. They develop at and below the greatest depths of which we have any knowledge. Such faults must, therefore, be closed fissures throughout their entire extent. Indeed they are often represented by a thin parting, a shearing plane, scarcely more than a knife-edge in thickness. In general it may be said that a thick fault breccia indicates a superficial fault, whereas a thin gouge is the evidence of greater pressure and therefore of greater depth at the time of development.

Faults appear at the surface of the earth, either because they have been exposed by erosion or because they are fissures that break through from a deeper origin. The oldest mountain making movements of the crust of the earth were accompanied by faulting, and the youngest are similarly conditioned. Indeed we must look upon faults as mechanical effects which are and always have been incidental to the movements of the earth, on a small scale and also on a scale commensurate with the dimensions of continents. One of the most striking manifestations of faulting which is now going on is the San Andreas rift of California. It has been traced more than 600 miles from the northern to the southern part of the State, and extends in the one direction northwest, into the Pacific Ocean basin, while it continues in the other into Mexico. There was a movement along this fissure in 1906 which caused a horizontal displacement of as much as 21 feet, with but slight vertical slip, and occasioned the disaster of the San Francisco earthquake and fire. Thus this fault may be described as an active fault in the sense in which we speak of an active volcano.

The horizontal displacement of 21 feet on the San Andreas fault in 1906 is only one of a very large number of such movements, whose total amount, although unknown, must be measurable by miles. The total vertical displacement amounts probably to many thousand feet. The San Andreas may therefore be described as a fault of notable magnitude and may be cited as a representative of a large number of faults which are recognized as elements of the structure of mountain ranges and of continents. Some such faults descend vertically into the earth's crust, probably to a depth of a score or two of miles, while others are known to dip beneath the surface at a very gentle angle and to correspond to horizontal displacements of many miles. It has been determined, for instance, that the northern Rocky Mountains have been

pushed eastward over the Great Plains at least seven miles. Such a fault is called an overthrust, and overthrusts are characteristic of many of the great mountain ranges of the world.

We have thus seen that faults may be large or microscopic. They may occur along fractures or shearing planes. They may lie at any angle to the horizontal, from 0 to 90 degrees, that is, from a horizontal to a vertical position. The direction of the movement in any case may also be either horizontal or vertical or in any diagonal line. Their investigation presents problems of very practical interest to the miner and of the most profound significance to the student of the larger structures of the earth.

Technical Discussion of Faults.—*We may define a fault as a displacement along a break or shear.* The essential characteristic of the structure is the displacement, the slip or shift of one part of a rock mass with reference to the other. An incidental, but necessary element of the structure is the break or shear on which the slip or shift takes place.

The break is usually a more or less irregular fracture, the course of which is influenced by the nature of the rocks through which it passes. It is, therefore, likely to change from an open fissure in hard rocks to a closed seam in soft rocks, or to vary in direction in passing from one to the other. If the rock mass is bedded or jointed, the break is apt to diverge into the bedding or jointing. Not infrequently one break will die out and another will come in somewhat offset, *en echelon*. All of these happenings are characteristic of breaks which originate in the uppermost rock masses or layers, within a mile or two of the surface of the earth.

The shear is a more regular fissure than a break. It is an effect of extreme pressure, under which the material yields on shearing planes. It commonly develops in soft rocks more perfectly than in hard and usually changes its direction in passing from one to another. Only under very excessive conditions of pressure from all sides does a shear pass straight through unlike masses. When most perfectly developed a shear is independent of the bedding or jointing of rocks, but it is not infrequently controlled by them. Shears are characteristic of the deformation of rock masses under great pressures, that is, at depths below those at which breaks occur.

The break or shear is the surface along which the displacement of a fault takes place. It is, therefore, called the *fault surface* or

fault plane. When a break is irregular and the corresponding fissure an open one, it becomes a zone of displacement and may be called a *fault zone*. Fault plane is the term in common use for both surface and zone, it being understood that plane in the mathematical sense can be applied to only small areas of the break or shear, but that the departures from a plane are relatively small as compared with the usually large area of the fault surface.

When a fault plane is inclined, so that one of the displaced parts lies above it, that part is called the *hanging* and its surface

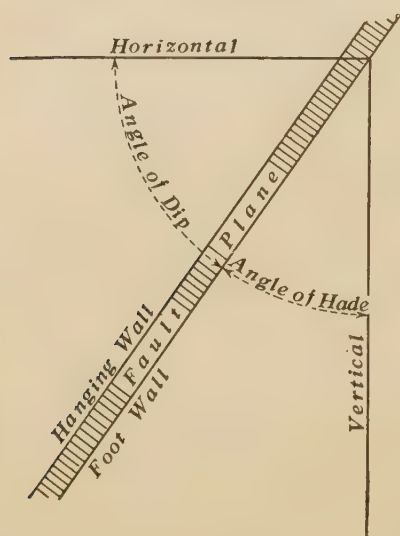


FIG. 39.—Diagram of the elements of a fault and the angles which define its position.

along the fault plane is the *hanging wall*. Similarly that part which lies beneath the fault is called the *foot* and its surface along the fault is the *foot wall* (Fig. 39). These terms originated in mining, and their significance is obvious as meaning that which hung above the miner or that upon which he stood.

The angle which a fault plane makes with a vertical plane (Fig. 39), is called the *hade* of the fault. It is an old mining term and its use illustrates the miner's habit of referring to the vertical shaft as a line from which to measure the attitude of any other line or plane. Geologists, on the other hand, habitually refer angles to a horizontal plane, and they speak of the *dip* of a fault (Fig. 39). The angle of hade and the angle of dip of any fault are complements of one another, their sum being 90 degrees. The smaller the hade the steeper the dip, and the gentler the dip the greater the hade. The word hade is also used as a verb, *to hade* meaning to incline toward.

Anticipating at this point in the discussion the consideration of the causes of faulting, we may recognize that the forces which are capable of producing faults are two in number and act at

right angles to one another. One is the force of gravity which draws everything vertically downward. The other is that hori-



FIG. 40a.—Normal faults in early Paleozoic limestone, Wacoba Canyon, Inyo Range, California. (Collected by C. D. Walcott.) The dotted layers are brittle limestone. The white layers are more clayey limestone and are less brittle.

The specimen demonstrates the limitation of fractures and accompanying faulting to the brittle layers. It shows how the blocks have tipped by slipping on the clayey base, leaving openings (black).

Size of specimen 2 inches by 5 inches. If we substitute miles for inches, the section would represent a section across mountain ridges produced by normal faulting.



FIG. 40b.—High angle thrust faults in limestone, exhibiting intense crushing. (Specimen in the Stanford collection.)

zontal force of compression which is also manifested in folding and schistosity.

Consider a landslide. It is caused by a parting or break along which a superficial part of a mountain slips down to a position of

rest. The break is a fault plane. At the top it is steeply inclined, but as the movement meets with resistance, which deflects it, the fault surface along which the displacement takes place becomes curved and tends to become horizontal. The effective force is gravity (Fig. 41). The fault may be called a *gravity fault*.

Gravity faults of the landslide type are not uncommon as superficial phenomena, and they probably occur more generally than is recognized among the faults of unexplained origin. A characteristic by which they may be distinguished is the fact that the surface is tilted back *toward the fault* by the rotation of the

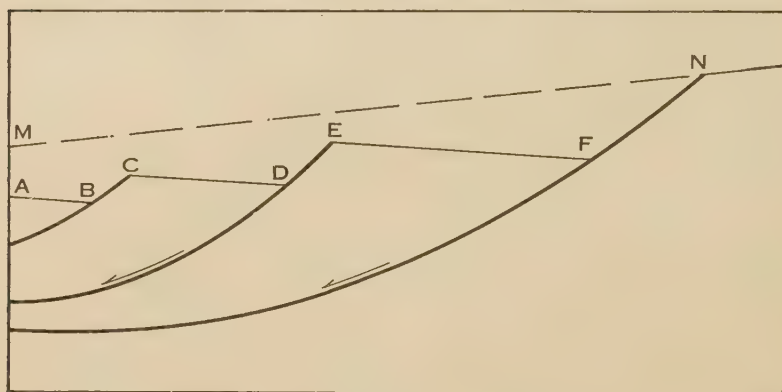


FIG. 41.—Diagram of displacement on normal faults of the landslide type, gravity faults.

Let *MN* represent the original surface and *AB*, *CD* and *EF* sections of the surface after faulting. The latter are inclined toward the fault in consequence of rotation of the masses on the curved fault surface.

block as it slips down the curved fault surface. Small terraces and ponds are formed in this manner high on mountain slopes (Fig. 41).

By way of contrast to the preceding let us now consider the effect of a very powerful compressive force acting horizontally at some distance below the surface of the earth and causing a horizontal displacement. The path of least resistance is upward, toward the surface, and the fault surface must curve in that direction. The case is mechanically similar to the movement of a landslide, but at right angles to it and in opposition to gravity. It is exactly the opposite of a gravity fault and because it is produced by a horizontal, thrusting pressure it is called a *thrust*,

But there are many kinds of thrusts and this type, in which the upward movement is predominant, is distinguished as an *upthrust*.

The block which is thrust up by an upthrust is rotated on its curved base, in a manner similar to but in a direction opposite to the movement of the landslide block. The obvious effect is to tilt the surface away from the fault. Upthrusts are sometimes of very great magnitude and the tilted surface may form a mountain slope. The western slope of the Sierra Nevada in California, for instance, which descends from an altitude of 7,000 feet evenly to some thousand feet below sea level, under the Valley of California, is a tilted plain, the upper surface of an upthrust block. The block is large and probably deep. Superficially it measures 350 miles in length and more than 100 miles in width. There is reason to guess its depth at 50 to 100 miles (Fig. 42).¹

Comparing the gravity fault with the upthrust we may note that they both approach a vertical position at the surface. Either one may be eroded back to a gentle slope, or the fault scarp may be modified by subordinate gravity faults or minor upthrusts. They are therefore difficult to distinguish on the fault surface or scarp, but the direction in which the block has been tilted affords a definite criterion by which they may be known as belonging to one type or to the other.

From this digression we may return to the subject of the direction of movement on the fault plane. In the gravity fault the displacement is assumed to be directly down the slope or dip of the fault plane, because that is the direction in which the force of gravity acts most effectively. The inclined plane offers a resistance, however, which diverts the movement from the direct vertical line of gravitation, and any lateral component of resistance will similarly cause the movement to take a diagonal course. In a like manner the compression which produces an upthrust may meet with resistances that will cause the displacement to leave the direct line toward the surface and take any course whatever, diagonally upward or even horizontal.

We are now in a position to consider the meaning of certain names which are in common use as applied to faults, and may first discuss the significance of *normal* and *reverse*. These are old terms which have outlived their usefulness, but they are so

¹ The fault which bounds the Sierra Nevada block on the east has long been described as a normal fault, but is now believed by some to be an upthrust.

firmly established in practice that there is little hope of their becoming obsolete. The best we can do is to attempt to define their proper meaning clearly and to point out the misinterpretations which theory has attached to them.

It happens that faults were first classified in the English coal-fields, where it is commonly the fact that the hanging has slipped down with reference to the foot (Fig. 43). That section of the bed of coal which is on the left in the diagram has slipped down with

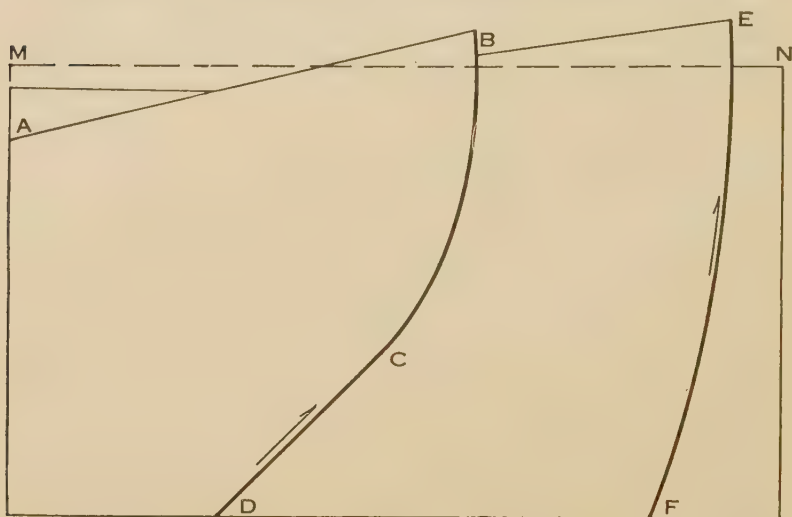


FIG. 42.—Diagram of displacements on upthrusts of the Sierra Nevada type.

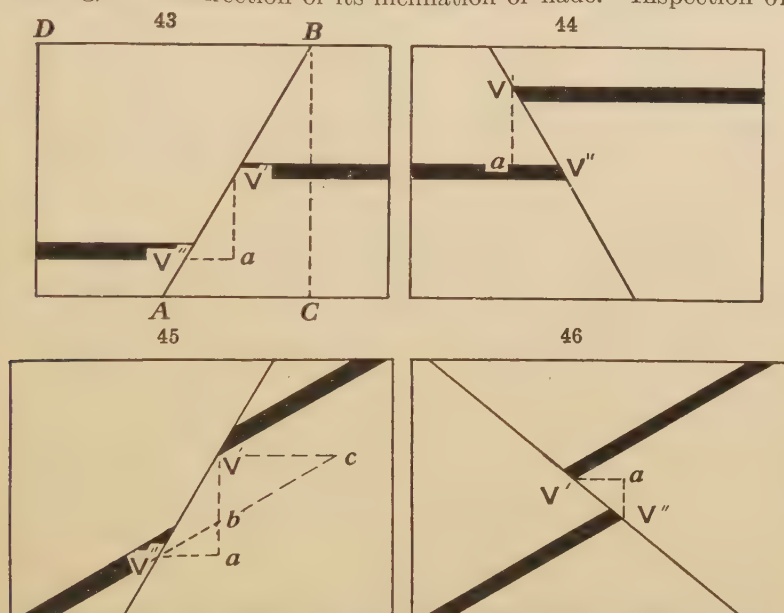
Let MN be the original surface and AB and BE be sections of the surface after faulting has occurred. Then AB and BE will be inclined from the fault in consequence of rotation on BCD and EF .

Note that it would be impossible to rotate $ABCD$ on BCD without displacing some portion of the adjacent mass or of BCD itself. Faults of this type are always accompanied by shearing, crushing and folding because the fault surfaces are not smooth uniform curves.

reference to the section which is on the right. The fault plane is inclined to the left, under the section which has slipped down. These relations are those which we would anticipate, on the assumption that the fault was due to the force of gravity, acting through the weight of the left-hand block. As this was a common occurrence in the English coal-fields, it became known as the normal thing and faults of this type were described as *normal* faults.

In certain exceptional cases it was found that the displacement had been upward, instead of downward, as in Fig. 44. That section of the coal bed which is on the right has been pushed up with reference to that which is on the left, and the fault is inclined to the right, under the part that has been pushed up. This is just the reverse of the normal displacement and was naturally called a *reverse fault*.

The most obvious fact about a fault, when it is encountered in mining, is the direction of its inclination or hade. Inspection of



FIGS. 43 to 46.—Diagrams of normal and reverse faults.

Figs. 43 and 44 will serve to show that the hade is different in a normal fault from what it is in a reverse fault, and this fact is used to formulate a rule by which they may be distinguished, as follows:

A normal fault hades to the downthrow, whereas a reverse fault hades to the upthrow.

The use of this rule in mining is evident. Let us suppose that the fault has been approached from the left and the point V'' has been reached. The miner is confronted by a blank wall, the fault plane. He observes its hade, which in Fig. 43 is toward him,

and he knows, perhaps, that the fault is a normal fault. Then, according to the rule, he has approached the fault through the down-thrown block and the continuation of the coal bed lies above. Or, let us assume that he has driven his tunnel from the right (Fig. 43), and having arrived at V' finds the fault hading away from him. It is clear that he is in the up-thrown block and the continuation of the bed lies below him, at V'' .

The correctness of his assumption, on which he proceeds to drive a slope through the solid rock, depends on whether the fault is really a normal fault or is in fact a reverse fault. If it be the latter, each of the inferences in the preceding paragraph is reversed, given the identical conditions, and the bed will not be found in the direction in which it is mistakenly sought. Hence the importance of knowing positively the nature of the fault, whether normal or reverse.

In the assumed case (Figs. 43 and 44), the fact that the strata are horizontal gives the problem the simplest possible aspect. The difficulties are not materially greater in the examples presented in Figs. 45 and 46, where the strata dip at a considerable angle, because in these simple sections it is implied that the displacement has been directly *down* or directly *up* the dip of the fault plane.

A somewhat different case is presented in Fig. 47, in which a bed or vein is shown as being displaced on the fault FF in such a manner that the segment on the right may be described as lying either *below* or *to the right of* the segment on the left. Take, for instance, a point V . It may have moved in the direction VV' or VH , or VV'' , or in any intermediate direction. Let VH be horizontal. Then we may say: If the displacement has been in any direction below VH , the hade of the fault plane is toward the downthrow and the fault is by definition a normal fault. But if the displacement is in any direction above VH , the hade of the fault plane is under the upthrow and the fault is a reverse fault.

If a miner were seeking the continuation of a vein, which continued indefinitely up and down, he would find it by driving his crosscut in the right direction from V . If, however, he sought the other part of a local bonanza, a misinterpretation might carry him above or below it and, striking the vein in a relatively barren

section by driving along VH , he would not know whether to go up or down to find the ore.

It will be observed, furthermore, that the force which has caused the fault is presumably different, according as the move-

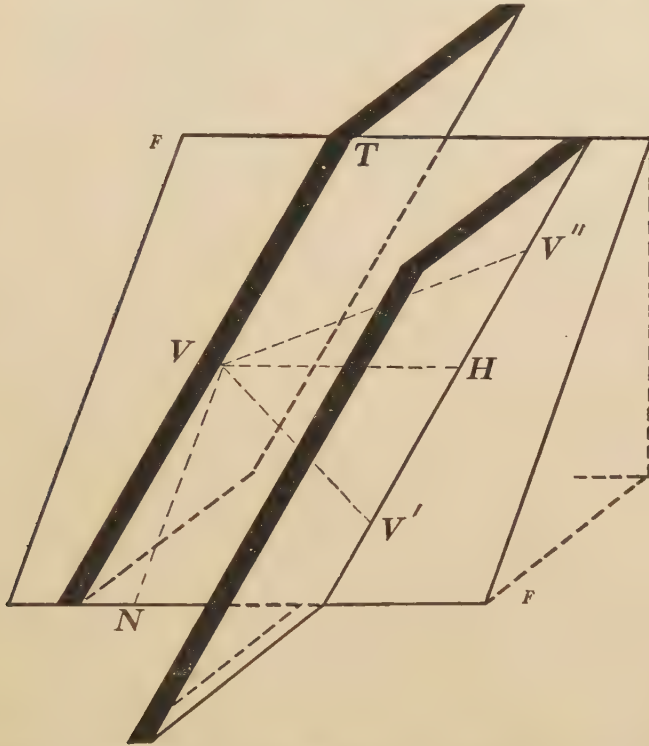


FIG. 47.—Diagram of a vein displaced by a fault which is apparently a normal fault, but which may be either normal or reverse according to the direction of movement.

VN is in a vertical plane and represents the displacement directly down the dip of a normal fault. Any displacement between VN and VH corresponds to a normal fault.

If the direction of movement were from V in any direction between VT and VH the fault would be an upthrust.

If the displacement were from V to H , the fault would be a horizontal fault, neither normal nor reverse.

ment has been below or above the line VH , that is to say whether it has had a downward or an upward directed component combined with a greater or less horizontal component. A downward com-

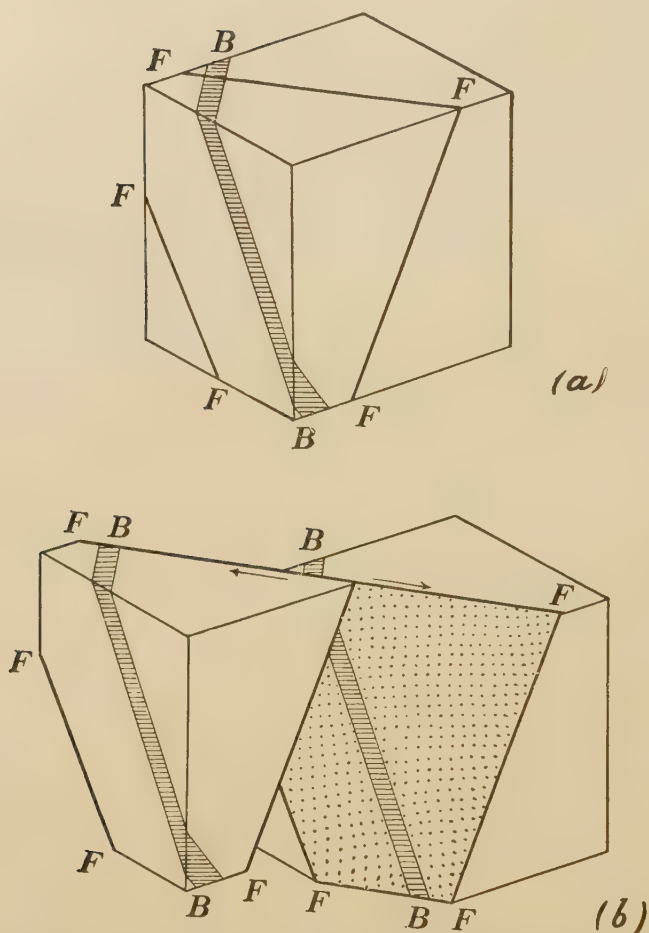


FIG. 48.—Block diagrams showing the effect of horizontal displacement in simulating normal faulting. (After Ransome. *Economic Geol.*, Vol. 1, 1906.)

(a) View of a cube of rock traversed by a dike and a joint plane, but not faulted.

(b) View of the same cube with the parts displaced horizontally. The dike, *BB*, appears to be thrown down and the fault plane fades under the downthrow, as in a normal fault, yet there has been no downward movement.

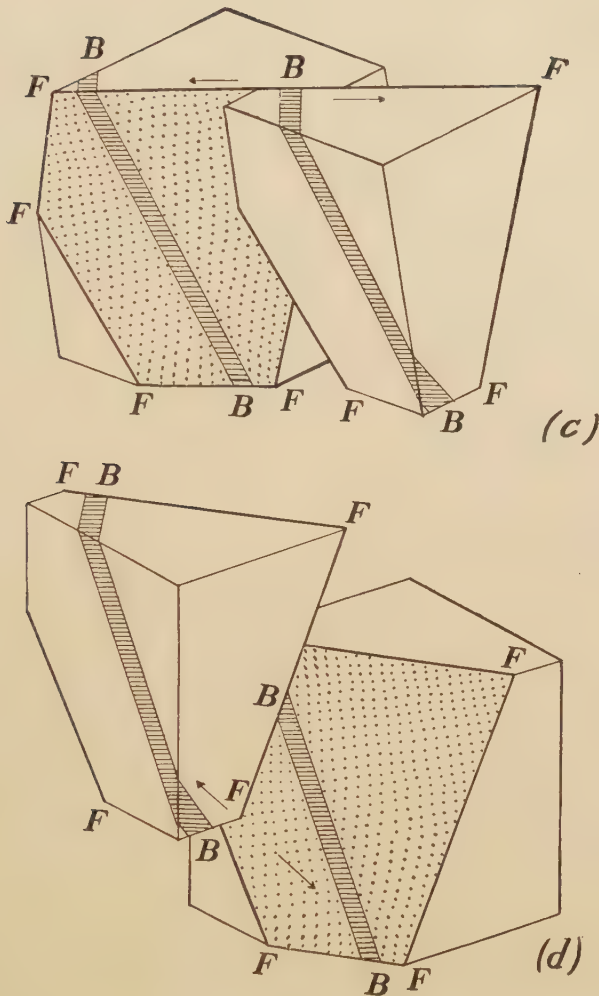


FIG. 48.—Block diagrams showing the effect of horizontal displacement in simulating normal faulting. (After Ransome. *Economic Geol.*, Vol. I, 1906.)

(c) View of the cube shown in (a) and (b), with a horizontal displacement which simulates a reverse fault. The dike *BB* appears to be pushed up and the fault plane hides under the upthrow, as in a reverse fault, yet there has been no upward movement.

(d) View of the same cube displaced diagonally by a movement between the horizontal and a direct upthrust, yet seeming to have suffered normal faulting.

ponent is due to gravity, which would tend to pull the displaced mass directly down, it is true, but which may be deflected by unequal resistances in the direction of the least resistance. An upward component, on the other hand, must be attributed to compression, which may be directed upward or diagonally as the resultant of various components of the force and the resistances. From the point of view of the theory of faulting, involving the nature and origin of the active force, it is important that the proper interpretation of the movements should be reached.

We may next turn our attention to the effect of faults in lengthening or shortening a segment of the rocks. By reference to Fig. 43 it will be seen that there is a gap between V' and V'' , which separates them horizontally. The length of the faulted segment has been correspondingly lengthened by the normal fault. On the other hand, in Fig. 44 we may observe that there is an overlap of the faulted bed, as is shown by the relative positions of V' and V'' , and the segment has been shortened by reverse faulting.

Putting these observations in the form of a general statement we may say: *Any segment of rocks which is parted by a true normal fault is lengthened (extended) horizontally, whereas any segment which is traversed by a reverse fault is shortened (compressed) horizontally.*

The word *true* in the preceding rule is to be contrasted with *apparent*. Defining a normal fault as one which leads to the downthrow, we must distinguish those which really do have that inclination from those which only seem to have it. For it has been shown in the immediately preceding paragraphs and in Fig. 47 that an inclined stratum or vein may apparently lead to the downthrow, when in fact it has a horizontal or a reverse displacement and is not a normal fault at all. The above rule must be applied with care.

It is not infrequently stated in discussions of the effects of faulting that normal faults are more common than reverse faults, and it is argued that there is consequently a notable extension of the earth's crust, of which account must be taken in any large survey of structural problems. The argument is weakened by the fact that a great many so-called normal faults are really reverse faults with a large horizontal component of displacement. Hence the number and importance of normal faults has been exag-

gerated. Furthermore, the two types of faults have separate regional distributions. There are large areas, plateaus and volcanic districts, where normal faults are typical and reverse faults are not developed or appear only as very subordinate features of the structure. In other regions, particularly in great mountain chains, reverse faults are the characteristic type of displacement and normal faults occur only as incidental structures.

It is dangerous also to generalize regarding the penetration of superficial structures far below the surface. Some normal faults, like landslides, pass by a curving fault plane into a horizontal displacement and do not affect the deeper rock masses. Others, and among them some of the greatest magnitude, are limited to plateaus, domed up masses which are stretched over a swelling base. The lengthening of the segment, even though the faults may be several hundred miles long and exhibit vertical throws of thousands of feet, is superficial. The body beneath the plateau is crowding up.

Since the inferences of the miner and the geologist regarding the effect of a fault, or its cause, are certain to be wrong if the movement is mistakenly interpreted, it becomes of prime importance to consider the means of determining the direction of displacement. They may be classified as general, local, and special.

The general considerations which may justify an inference as to whether a fault is normal or reverse relate to the nature of the deformation throughout the district or province in which the displacement has occurred. Where folding and jointing are the dominant phenomena, reverse faults may be looked for and any apparent normal fault should be challenged until positively identified as such.

To cite certain illustrations, we may mention the folded zone of the Appalachians, where normal faults are practically unknown, or the strongly upthrust and overthrust ranges of the Rocky Mountains, where the nearly vertical upthrust faults have too often been classed as normal, simply because they had a small hade. On the other hand, normal faults are characteristic of the Colorado plateaus, so graphically described by Powell and Dutton. In a plateau region folding is an incidental effect and reverse faults, if any occur, are very exceptional and local. Regions of what may be called mixed structure are illustrated by the Coast Ranges of California, where the dominant effects of compression,

exhibited in upthrusts, overthrusts, and folding, are associated with normal faults, due to the tension of arched superficial beds or to the disturbance of equilibrium caused by uplift and tilting.

The local evidences of the direction of movement on a fault plane are those which appear in the displacement of related strata or dykes or other recognizable datum planes. The problem usually takes the form of identification of a fault encountered in mining or in geologic surveying with its extension in adjacent territory, where it may be more widely examined and the ends of a displaced stratum may be located on either side of it. Suitable surveys then suffice to determine the amount of the displacement between the exposures of this one datum plane and, given the line of movement, the displacement in any other direction on the fault plane can be determined mathematically. Practical problems of this nature are treated in the appropriate section, pp. 238-254.

The required solution of the problem in these cases may be merely qualitative or quantitative. That is to say, it may be sufficient to determine the direction of movement, as between two possible directions, or it may be necessary to ascertain the amount of displacement in a particular direction and place. In case the movement on the fault plane was one of simple translation, all parts moving parallel to one another, the measurement involves no difficulty. If, however, there has been rotation of one block upon another, the solution becomes more difficult and demands that the displacements of at least two established points be known. Rotation is more commonly a factor in fault movements than has usually been recognized and should be looked for rather than neglected. Where there has been rotation, it is important that the data upon which a solution is based should be concentrated in as small an area as possible, to reduce the possibilities of error.

Direct evidences of fault movement are observed on the fault plane itself or in the immediately adjacent rock. They consist of the effects of mechanical work done on the rock faces as they mutually pressed, crushed, and molded one another in dragging past. They may be described under the terms: *polish*, *scratches*, *striae*, *furrows*, and *grooves*; *chatter marks*; *crushing* or *mashing*; *plucking*; *shearing* and its effects, *jointing*, *crescentic gouges*, and *gash veins*; *drag* and *drag folds*.

Scratches, *striae*, *furrows*, and *grooves* are engraved or plowed lines, produced by a fragment or corner of hard rock penetrating

the opposite surface as it is dragged along. The four words are used in their usual English senses: a scratch, a mere scratch, lacking significance; striæ, a number of lines, arranged in parallelism or in intersecting systems; furrow, a plowed depression of linear dimensions, but wider than a mere line and hollowed out by the removal of material; groove, a broad depression, produced by the removal of material or by pressing it aside, generally rounded on the bottom and often without definite margins.

A scratch is made by a point projecting from the opposite face. It starts where the point comes into contact and it changes its character as the point is worn down or as it is lifted off. If worn down the point broadens and the scratch widens in the direction of motion. Several scratches may thus join to form one broad one. If lifted off the point may cease to scratch gradually or suddenly, but to do so requires space between the faces, which can only be separated by the meeting of opposite shoulders. The shoulders should appear as higher surfaces on either one or both sides of the scratch and may very likely be highly polished. It is possible that the scratching tool may be rolled along and so leave a trail of scratches and pits. It does not appear that such marks would obey any rule. Or the tool may be crushed and begin to make several scratches, which would spread out in the direction of advance.

Striæ, in distinction to scratches, are more regular and more persistent. Nevertheless, we may describe them in the words of Chamberlin,¹ who in writing of glacial striæ says:

Striæ differ widely in respect to the perfection and character of their definition. This apparently resulted partly from the form of the cutting tool, partly from the looseness or firmness with which it was held, partly from the smoothness or roughness of the surface in which it was inscribed, partly from the texture and lamination of the rock, both of the tool and the bed, and partly from the rate and irregularity of the motion.

Striæ may be interpreted as scratches with reference to the direction of movement, blunt ends and diverging lines advancing. It is to be noted, however, that if the surface is wavy at right angles to the striations, the pressure of the tool may have varied in a manner to modify the character of the lines.

¹ CHAMBERLIN, T. C., *Rock Scorings of the Great Ice Invasions*. U. S. Geol. Surv., *Seventh Annual Rept.*, p. 216, 1888.

Furrow is a word which implies that the material has been turned out to one side forming a ridge beside the valley. We cannot expect the ridge to survive on a fault plane and the valley which remains is simply a broad scratch. It seems possible, although the writer has never observed it, that the margins of a furrow may show distinctive effects of plowing or dragging. Plowing implies the action of a tool which projects forward and would rip up slivers which would point backward and be broken off at their thicker, forward, end. A dragging tool, on the other hand, would tear out loose irregular pieces, whose form would be governed solely by the structure of the furrowed rock.

Grooves may be wide furrows with a rounded cross-section, where material has been ground off, or they may be molded grooves such as a finger makes when drawn over a mass of putty. The furrow groove does not differ from other furrows except that it may exhibit chatter marks or crescent-shaped fractures, which are described further on. The molded groove is characteristic of the molding of the surface of the more yielding rock mass to fit the irregularities of the opposing face, which may be of the same or of harder material. The effect is quite different from that of scratching, since the modeling may be accomplished by yielding to a considerable depth in the mass without breaking the surface.

The molded groove is an effect of plastic deformation and may vary from a fine line to a flat, spreading hollow. It may be straight or curve around the outlines of a raise. The sides may overhang. Large grooves often comprise many smaller ones. All the surfaces are rounded and in cross section pass into one another smoothly.

Molded grooves tend to be parallel among themselves, but they do fan out and in such cases the divergence is commonly, if not universally, in the direction of the forward movement of the opposed face.

Hard particles, such as pyrite crystals in slate, or masses, such as concretions, chert nodules, or niggerheads, tend to remain in relief on the modeled surface. They then present a push side to the movement, resisting it, and have a lee side, which is protected from it. Two types of ridges result, the *spur* and the *trail*.

The spur points from the hard particle backward toward the advancing, opposite face. It consists of the softer rock material which is packed against the obstruction. It lies in the re-entrant angle which is formed by the over-riding face as it rises over the

resistance. In this position the spur is exposed to the full pressure of the advancing face and is therefore usually highly polished. Its form is that of an acute cone, which lies with the apex directed backward. Molded grooves divide at its apex and pass around the obstruction, diverging forward.

The trail is a ridge which survives in the lee of a hard particle or mass, by which it has been protected from the over-riding face. Its base lies against the protecting block and it extends forward, gradually diminishing in height and possibly in width as it gets out from under the lee. It may be polished, but is often less smoothed or even left rough, because it is not so severely squeezed. The molded grooves which pass on either side of the obstruction tend to continue parallel to one another beyond it and thus give to the trail a cylindrical form.

Chamberlin describes trails as most characteristic of glaciated surfaces, and mentions an example of a spur as an exceptional development.¹ The spur would seem to be of more common occurrence on fault surfaces, and for this reason: beneath a glacier the projecting boulders dig away the rock surface, much as a chisel digs into wood, and they clear away the material up to the obstruction, as the chisel cuts up to a knot. The spur has no chance to form. But where one face of a fault is pressed into another with a force that molds them mutually into one another, there is no digging. An obstruction lifts one surface off of the other, forces them apart, and leaves a space in which material may remain or into which it may be squeezed by the excessive pressure on either side of it. Thus the spur is formed.

Chatter marks are fractures which occur in deep furrowed grooves or gouges and, being a mechanical effect due to the gouging, are limited in occurrence to that association. They cross the groove at right angles, but are curved and present the convex side toward the rear in the direction from which the gouging point moved. Chamberlin describes them as very characteristic of large glacial grooves.²

Crushing is a common effect of excessive pressure on the surfaces of hard rocks, like quartz, and takes the place with them of the modeling produced in softer rocks. A crushed area may well be called a *bruise*. The rock is more or less minutely granulated

¹ CHAMBERLIN, T. C., Rock Scorings of the great Ice Invasions. U. S. Geol. Surv. *Seventh Annual Rept.*, p. 245, 1888.

² *Op. cit.*, p. 247.

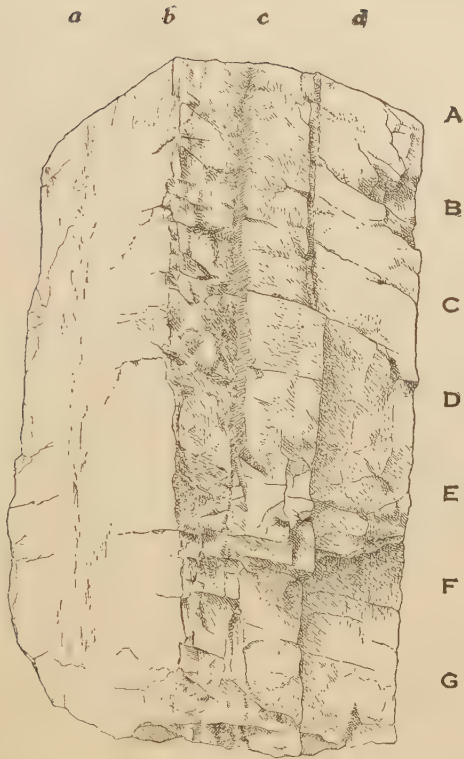


FIG. 49.—Specimen of vein quartz, showing a polished surface, and illustrating the criteria for determining the direction of movement on a fault. These criteria are as follows:

Considering first the large drawing representing the polished surface, when the fingers are drawn over this surface, in the direction from *A* to *G*, the surface feels perfectly smooth. If they are drawn over it in the opposite direction, the fingers encounter sharp projecting shoulders. This indicates that this surface has moved from *G* toward *A*, relative to the other side of the fault.

At *A-d* may be noted an irregularity or bruise which starts in a point, and broadens until at *B-d* and *C-d* it is considerably wider. This has been made by some projection on the other surface of the fault plane. To apply the rule, the projection moved from the narrow point toward the wider part of the bruise, deepening and widening it as it progressed. In other words, the block pictured moved toward the point of the bruise, or from *G* toward *A*, thus confirming the statement made above.

At *C-d*, or a little below it, is a hollow, with a steep side toward *A*, and a gentle slope toward *G*. At *C-g* is seen another similar hollow. These are due to plucking, the material removed having been carried away from the steeper side, again showing that the pictured block moved upward relative to the other side of the fault.



Turning now to the end view of the specimen, we see running from *C*-*c* to *D* a curved fracture, which makes an acute angle with the under surface, pointing downward. There are several other fractures parallel to this one. We can now think of the specimen as a block in a fault, with the masses on either side moving in opposite directions. If our conclusions regarding the direction of movement on the large face (*a* to *b* in the end view) are correct, the mass to the left of the specimen moved downward, hence the mass to the right must have moved upward. The fractures make a fairly high angle with the surface, and are not straight, nor are they clean cuts. This would indicate that they are tension cracks, developed by the drag on the fault surfaces. In such cracks, the acute angle points toward the direction in which the fractured block moves. This indicates that the under surface moved down relative to the mass to the right of the specimen, and the left-hand surface, that pictured in the larger drawing, moved up, from *G* toward *A*, again confirming the original conclusion.

These tension cracks developed by friction must not be confused with shear planes, which develop due to compression and movement. Such planes are generally more regular, straighter, and make a smaller angle with the surface. The danger of confusion lies in the fact that shear planes point in the opposite direction, relative to the direction of movement, from that assumed by the tension fractures. That is, if they were developed in this case, they would point downward to the left, instead of to the right.

and the surface depressed. If it be assumed that the bruise was caused by a prominence of the opposite face, which in turn was also crushed as it advanced, then the area of excessive pressure should widen in the direction of movement. Thus a bruise, if it have an elongated and triangular form, indicates the direction of displacement.

Mashing is a term which was introduced by Van Hise to cover the effects of excessive granulation by crushing, accompanied by the displacement of the granules and often by recrystallization involving flow of the rock. When crushing passes into this extreme stage the surfaces are molded to each other and the effects can no longer be distinguished by the eye alone from molded grooves or hollows.

Plucking is an action by which particles or pieces of the face are torn out and carried away. The term is borrowed from glacial geology, where it is used in the same sense, but for larger masses. It is a common action of glaciers because the ice not only grasps, but embraces exposed blocks and takes them with it. Plucking from a fault face is the action of excessive local pressure and implies that in front of that great pressure there was a condition of less resistance or a space, in consequence of which the loosened piece could leave its bed and be carried on. Plucking, therefore, takes place on the lee side of an obstruction to the movement, and the piece plucked out may include a part of the obstructing body. Thus a spur may lead up to a blunt, broken end, from which the hard particle that caused the formation of the spur has been plucked off. Or where a miniature fold has been raised across the line of movement, the layers on the farther, advanced, side are often torn away.

Plucking from crushed surfaces may also occur where there is no apparent obstruction to the advance of the opposite face. In these cases a dislodged piece of rock has been pressed down in the rear and raised in front by an advancing prominence of the opposite face. Often the piece is merely rotated in its bed and remains inclined backward at a slight angle to the polished face. This kind of plucking may be observed in various stages of development on bruised quartz surfaces.

A piece plucked out is usually broken off and therefore leaves a rough bed. In this respect plucking differs from shearing. The rear side of the hole left by plucking is in the lee and retains

its roughness, especially if it be steep. The advance side of the hole, on the other hand, is exposed to abrasion and is often smoothed or polished. This is a common means of determining the direction of advance of the opposite face. Even when the roughness cannot be distinguished by eye, the finger will feel the difference between the upstanding rear faces and the worn down front margins of the small cavities in the polished surfaces of hard rocks. In a bruised face, in which the bits of rock may have



FIG. 50.—Specimen of quartz vein showing slickenside with molded and polished grooves. The plucked surfaces indicate that the movement of the overlying mass was from left to right. Four-fifths original size.

been but slightly pushed forward and raised in front, it is also possible to recognize the difference. The finger should be held at right angles to the direction of movement and passed gently back and forth.¹ Care should be taken not to confuse a plucked hollow with a crescentic gouge, as the two present the steep facet of the depression in opposite directions. The plucked hollow is, however, much the more common.

¹ I am indebted to my colleague, Professor C. F. Tolman, Jr., for calling my attention to the delicacy of this test in the case of polished quartz surfaces.

The crescentic gouge is an effect of *conoid fracture*, according to Gilbert,¹ or of shear, which has a distinct form and interpretation. It is produced by pressure against a surface which is inclined backward, toward the opposing face, and which yields by a fracture similar to that which would be produced by a blow (conoid fracture) or by shear. The distinction is difficult and for the present purpose unimportant, since the form would be the same. The fracture or shear inclines forward into the rock at a gentle angle and is concave upward in cross-section. A sliver or flake is thus loosened from the face and may be broken off at the butt end, leaving a vertical fracture. The latter, which is ordinarily curved, faces the direction of motion and presents its concavity toward it. It is thus oriented in a position which is the opposite of that of a plucked hollow and of chatter marks. Crescentic gouges may be looked for on the push side of a rise where the surface is inclined toward the opposing face, which moves against it.

It is evident that a fault movement will displace any older system of joints and may open or close any contemporaneous system. Thus there are several cases which may be distinguished; namely:

- (a) The joints were older than the plane of parting on which displacement subsequently occurs.
- (b) The joints developed after the plane of parting had been produced, as a result of pressure against it, during an initial episode of dislocation, but they have been displaced by later faulting.
- (c) The joints were contemporaneous with the initial movement on the plane of parting and their development has been influenced by the stresses set up during faulting.

When the joints were already in existence before the fault plane originated (*a*), they are common to the country rock on both sides of the fault, subject in their development to such vari-

¹ GILBERT, G. K., Crescentic Gouges on Glaciated Surfaces, *Bull. G.S.A.*, vol. 17, pp. 303-314, 1906.

Note.—"Gouge" is here used in the sense of a groove and not as miners use it to designate clayey selvage.

ations of lithology as it may present. They will be displaced by the fault movement, either by a simple motion of translation along the fault plane, or by rotation on the fault plane, or by translation and rotation combined. The criteria which joints offer in this case for determining the direction of movement are similar to those afforded by any other older structure, such as bedding, for instance.

When the joints were developed *pari-passu* with the plane of parting, as is assumed under (b) and (c) both, they start from that plane and are likely to be limited to its vicinity. If they existed before a later movement took place (b), they were actually older structures when that movement occurred and they may be obviously displaced by it. The evidence is to be sought in their angular relation to the fault plane, in their dislocation, and in the dislocation of any mineralization that may have occurred on them.

If the joints develop during the progress of faulting they are due to pressure against the fault plane. That pressure will be perpendicular to the fault plane, no matter what the angle of incidence of the general pressure in the rock masses may have been, for any general pressure is resolved on a plane of motion into two components, parallel and perpendicular to the plane. Jointing is produced by the perpendicular component.

A pressure perpendicular to a plane tends to produce two sets of joints oriented symmetrically with reference to the pressure and the plane and making angles of 45 to 60 degrees with the direction of pressure. The angle between the joints and the plane may thus vary from 45 to 30 degrees, it being the complement of the angle between the joint and the pressure (see discussion of shear, page 166). The angles will approach 45 degrees in hard rigid rocks and will depart from 45 degrees in softer rocks in proportion to the plasticity.

The preceding paragraph relates to an ideal case, which is rarely realized because it neglects friction and friction is a force which modifies the effect of the perpendicular component by combining with it to form an inclined resultant. Thus in Fig. 51: Fr represents friction, P_2 the perpendicular component, and R the resultant. Let FF represent a fault plane; P the force causing displacement; P_1 and P_2 the components of P ; F the value of friction in the hanging wall; R the resultant of F and P_2 in the hanging wall. Then shearing stresses will be set up in

pressed closely together and moved past one another, provided one or both of them be plastic or flexible. Massive, rigid rocks do not show the effects of drag, since when stressed beyond the elastic limit they yield by shearing instead of by plastic distortion or bending.

Plastic distortion is characteristically developed on the surfaces of clay rocks. They become smeared over the fault plane, sometimes taking a very high polish, sometimes forming a layer of gouge, which obscures or even prevents the development of significant markings.

The thinning out of the overturned limb of an anticline, which may go to the extreme of thrust faulting, is a form of drag that is often a phase of plastic distortion accompanied by minute shearing, as was first pointed out by Heim¹ (Figs. 20 and 21). In the development of schists, by the rotation of mineral particles into parallel positions and by the growth of new minerals with parallel orientation, we may recognize the extreme effects of drag in materials which are plastic in the sense that they may be distorted without fracture. These phenomena may be limited to a fault plane, or occur throughout a fault zone, or pervade large masses of schist, but in all cases there have been displacements, either local or distributed, which constitute faults, and the effect is one of drag. Unfortunately these plastic effects are usually not significant criteria of the direction of movement.

Drag becomes significant when it involves bending or folding. Where a fault traverses strata, the ends are commonly bent back with reference to the direction of movement of the block in which they are, or forward in the direction in which the opposite face has moved. Since this is true of both sides of the fault, but in opposite directions, the ends bend toward one another and may become tangent to one another, parallel to the fault plane (Figs. 20 and 21). The extreme development of this form of drag is characteristic of thrust faulting, where the pressures are very great, but the ends of strata may also be bent in displacements occurring on normal faults, the weight of the downthrown mass being sufficient to cause the flexure.

In faulted sedimentary or other bedded rocks the deflection of strata in consequence of drag is one of the most valuable criteria by which to ascertain the direction of displacement. It is illus-

¹ "Mechanismus der Gebirgsbildung."

trated in Figs. 52, 58, 60, 62 and 66. In Fig. 52 we have the unusual case of the drag in the same direction on both sides of a normal fault. As the simultaneous deflection of the opposed sides in the same direction is not possible, it was with reason assumed that there have been two episodes of movement on the one fault plane at different times. This conclusion, originally reached by Walcott,¹ has been confirmed by Noble² and may

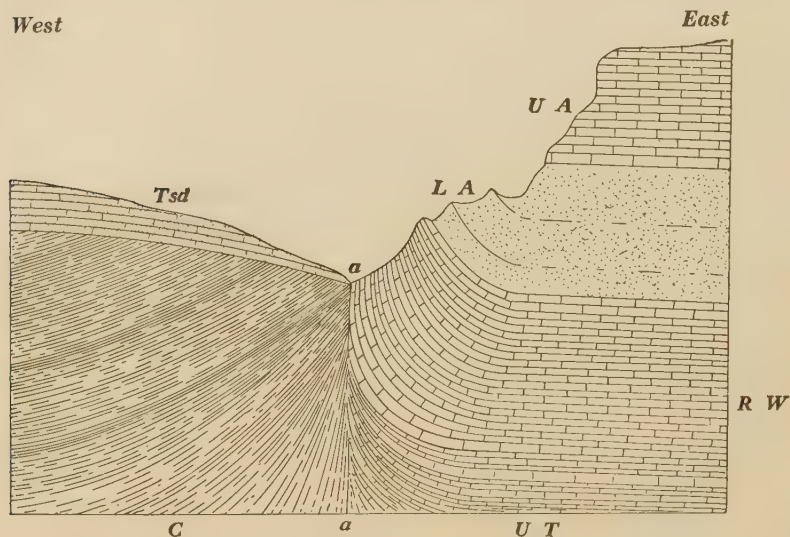


FIG. 52.—Section showing the effect of drag on a fault on which there have been two movements in opposite directions at widely separated times.

aa, Fault line. The mass to the left of *aa* consists of pre-Cambrian rocks capped by *Tsd*, Cambrian "Tonto" sandstone. The drag in these rocks shows that the left-hand block subsided in a pre-Cambrian movement.

The strata on the right are Paleozoic (*R. W.*, "Redwall," *L. A.*, "Lower Aubrey," *U. A.*, "Upper Aubrey"). The drag which they exhibit shows that they have been thrown down relatively to the left-hand block, by a post-Paleozoic movement.

serve to show how unequivocal is the interpretation of the bends assumed by strata in approaching a fault.

Where a fault plane lies nearly or quite parallel with the bedding

¹ WALCOTT, CHAS. D., Study of a Line of Displacement in the Grand Canyon of the Colorado, in Northern Arizona, *Bull.*, G. S. A., vol. I, pp. 49-64, 1890.

² NOBLE, L. F., The Shinumo Quadrangle, U. S. Geol. Surv., *Bull.* 549, 1914, p. 39.

of a faulted mass, as it often does in stratified, slaty, or schistose rocks, the dragging of one stratum over another may produce local folds, known as *drag folds*.

A drag fold on a fault plane usually consists of an anticline and a syncline, comprising three limbs. The fold is unsymmetrical or overturned, with the steeper or overturned limb facing in the direction of movement of the over-riding mass. In thin bedded shales and slates or laminated schists, drag folds are often very small or microscopic. They frequently pass into overthrusts, which take the orientation of shearing planes, lying at an acute angle, less than 45 degrees to the fault plane, with the apex directed forward with the overthrust mass.

Drag folds are also common in shales which are involved in large anticlines and become distorted as heavier beds adjust themselves to the folding. As the strata move past one another, as great thicknesses bend, the outer ones crowding up out of the synclines toward the anticlines and the inner ones pushing from under the anticlines down under the synclines, any thick bed of shale becomes a zone of displacement. It is dragged in opposite directions on its upper and lower surfaces and is forced into a system of drag folds, which are much more complex than the major structure of which they form a part. In these cases the drag folds are usually overturned and often overthrust, and always in the direction of the crest of the great anticline. This is an important means of determining the position in a fold of a body of strata, which may be so isolated or unidentified that its true stratigraphic position is in doubt. Drag folds on a large scale were first described by Heim¹ (Fig. 63).

High- and Low-angle Faults.—It has been emphasized in the preceding pages that it is often difficult to distinguish a normal fault with a steep hade from an upthrust fault, which may be equally steep, and also that normal faults may curve out from the steep attitude which they usually assume and, approaching a horizontal position, may simulate thrusts. In the absence of positive evidence, which is frequently not available, it is unwise to commit oneself to the statement that a fault is or is not a normal displacement, because that statement carries with it inferences that are seriously misleading, if erroneous. It is, therefore, desirable to have non-committal terms, by which faults may be

¹ "Mechanismus der Gebirgsbildung."

described, for use in those numerous instances in which the true character of the structure remains uncertain.

The terms *high-angle fault* and *low-angle fault* are here introduced for that use. In the following descriptions of faulted regions the designation high-angle will be employed for faults whose attitude is steep; that is, they have a hade which is less than 45 degrees or a dip that exceeds 45 degrees. Low-angle, on the other hand, will be used to designate that class of faults whose hade is greater or their dip less than 45 degrees.

This distinction is simply one of position and has nothing to do with the nature of the fault, whether normal or reverse, since there are reverse high-angle faults and also normal high-angle faults, and low-angle faults may be either reverse or normal. The position of the fault plane with reference to the vertical or horizontal does not indicate the character of the force, whether tensional or compressional, to which the displacement was due. Thus the terms high-angle and low-angle are free from any ambiguity or undesirable implication as to the causes of faulting. They represent an observed fact and they express an important geometric relation, which fixes the trace of the fault outcrop on the topographic surface or the extension of the fault underground.

Some High-angle Faults.—The following descriptions relate either to certain classes of high-angle faults or to districts where such faults are characteristically developed. Some of the faults described are typically normal, others are upthrusts, and still others are indeterminate.

High-angle faults of small displacement and purely local extent are common in sedimentary deposits. They may result from any condition of unequal subsidence in the course of burial and consolidation, or from any disturbance of equilibrium which causes one bed to slip on another after the fashion of a landslide. They are gravity faults and have normal displacements, which vary in amount from a fraction of an inch to a hundred feet or more.

Horizontally bedded sandstones, which overlie shale beds, are not infrequently faulted in this manner in consequence of the unequal subsidence of the shale, either before or after consolidation, under excessive load.

Glacial deposits exhibit normal faulting which results from the melting of buried ice blocks. The overlying strata of sand and

gravel sink in, sometimes in a series of parallel normal faults like steps, sometimes on converging faults which define the dropped wedge, forming a small trough fault.

In volcanic regions the outflow of lava from beneath horizontal beds or from under a dome results in displacements which are very similar to those that may be seen on a small scale in glacial deposits; but the lava masses are often very large and the faulting to which their movements may give rise is sometimes characteristic of an extensive region.

Ransome¹ has described an example which presents complex faulting, presumably due to the intrusion and extrusion of lavas (Fig. 53).

The rocks of the Globe region comprise both sediments and igneous rocks, and they range in age from exceedingly ancient (pre-Cambrian) formations to the most recent continental deposits. The igneous rocks occur as intrusives in the pre-Cambrian and Paleozoic sediments and also as extrusives of Tertiary and Quaternary age. That is to say, the region has repeatedly been invaded by molten rock, which has risen toward the surface and in some cases at least has flowed out over it, leaving the superficial crust unsupported. The latest occurrence of this kind is very recent.

Faulting has resulted. It is very irregular in strike and dip, as this type usually is. Ransome distinguishes two groups, those having a generally northeast-southwest trend and those striking approximately northwest and southeast. The dips may be to either side of the strikes and range from 50 to 90 degrees with a tendency to approach 75 degrees. Faults belonging to these two systems are the more conspicuous, but they are associated with

countless other fissures running in all directions and adding greatly to the complexity of the fault network. It has proved impossible to reduce these generally subordinate fractures to distinct groups or systems. The region has not been dissected with mathematical precision along determined lines, but has been shattered by complex geological forces to an extent that is only less difficult of analysis than is a pane of shivered glass.

The principal displacements occurred after certain eruptions of dacitic lava during the Tertiary. They are normal faults, so

¹ RANSOME, F. L., U. S. Geol. Surv. *Geologic Atlas of the United States*, Folio 111, Globe, Arizona, pp. 11-12 and maps, 1904.

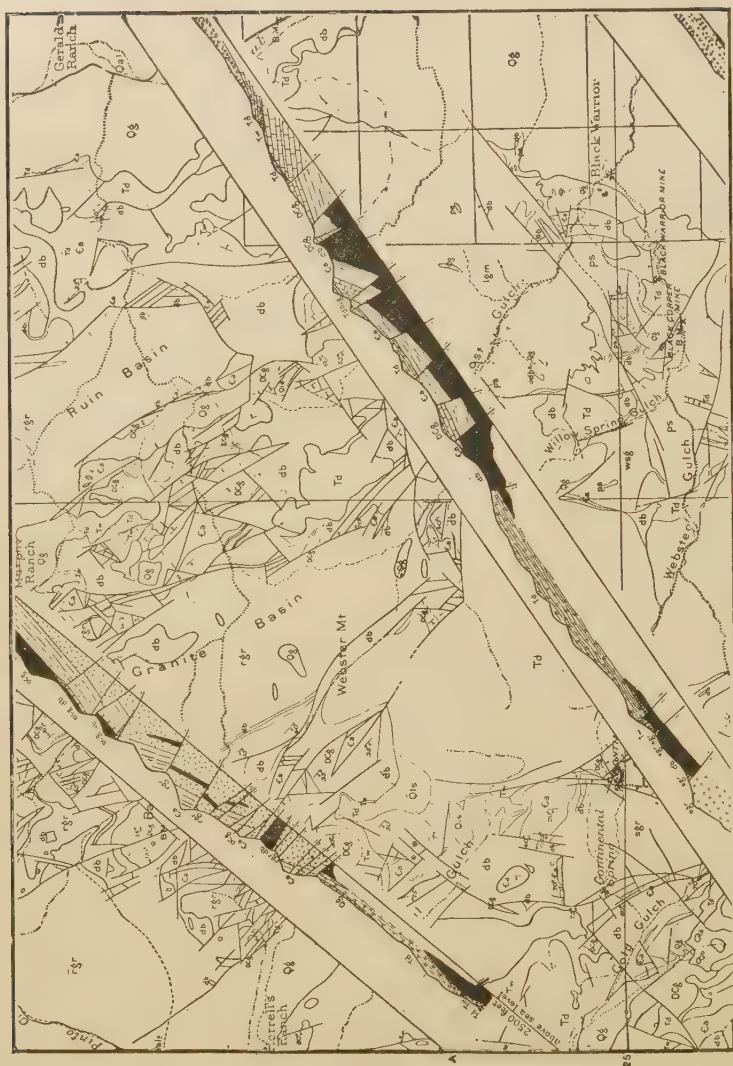


FIG. 53.—Faulting in the Globe District, Arizona. (After Ransome.) Illustrating the type of normal faulting, characteristically developed in regions of volcanic activity marked by the extrusion of lava flows.

far as their character can be determined, and there is a conspicuous absence of folding or thrusting. While it is impossible to quote as fully as one would like from Ransome's detailed description, the following may be taken from his explanatory statement, since it is probable that it is the correct interpretation of the causes of faulting in many other volcanic regions:

The faulting of the Globe region is most satisfactorily accounted for by supposing stresses acting in directions more nearly vertical than horizontal, such as would result from differential elevations or subsidences over the area. . . . The causes are deep-seated and inscrutable. It is suggestive that here, as in the San Juan region of Colorado, the later fissuring followed or was correlated with an extensive transfer of volcanic material from its subterranean source to the surface. It is probable that there is a more direct connection between such volcanic paroxysms and the subsequent fissuring. The earlier, structurally less conspicuous, but economically more important, post-diabase dislocations were also preceded by great eruptive activity, and it is reasonable to regard this faulting also as a phase of regional readjustment after the widespread disturbances effected by the intrusion of the diabase.

Although it is true that the faulting of the Globe, as of similar districts, cannot be reduced to order by any mechanical analysis, it must not be assumed that the fractures follow no law. Unequal elevations and subsidences produce torsion and torsion results in systematic fractures in rigid, elastic bodies like rocks. If we could know all the conditions the phenomena would be found to be the results of reactions according to law and, in specific, limited areas, such as an individual mine may embrace, the system might advantageously be worked out. The common association of normal faults of this character with volcanic eruptions, which are also related to mineral deposits, gives to the fault type a peculiar economic interest.

High-angle, normal faulting of a large and simple type is characteristic of plateaus. It is there associated with and developed from monoclinal flexures. Gilbert, Powell, and Dutton were the first among American geologists to observe this relation.

Dutton¹ says:

¹ DUTTON, C. E., Report on the Geology of the High Plateaus of Utah, Dept. of the Interior, U. S. Geog. and Geol. Survey of the Rocky Mountain Region, J. W. Powell in charge, chap. II, p. 25 et seq., 1880.

The great structural features of the High Plateaus are the faults and monoclinial flexures. . . . All of the greater displacements of the district present certain well-known habitudes. Most important among them is the strict homology of the faults with the monoclinial flexures. In truth, so close is the homology, that we are justified in calling a monocline in some of its aspects a modified fault. The only difference for structural purposes is that in the case of a typical fault of the simplest form the shearing is along one plane, while in a monoclinial the shearing lies between two planes. We also have cumulative or repetitive or "step-faults," where the shearing is subdivided among several planes. All have this in common, that the passage from the uplifted to the lowest thrown side is through a very narrow zone, which has its width reduced to zero in the case of a single or simple fault. All of the great lines of displacement assume all of these modifications in different parts of their extent. In one place the fault is simple. A few miles further along its course it may become subdivided into a series of step-faults, still further on, into a perfect unbroken monoclinial; it may be at another locality a faulted monoclinial—a part of the displacement being through flexing and a part through shearing. In any case the effect in its broader aspects is the same. One side has been uplifted, the other side "thrown." Another striking characteristic of these displacements is their systematic arrangement. Viewed in one way they approach parallelism, but there is a noticeable convergence of the lines as we trace them from south to north. . . . In the Grand Canyon district (where they give origin to the Kaibabs) the belt of faulted country is wider and the intervals between the faults and flexures are greater than in the High Plateaus. This width diminishes northward, and several of the grander faults at length become merged into one vast monoclinial flexure, forming the western flank of the Wasatch Plateau.

The magnitude of the faults is great. They vary in length from a score of miles to 300 miles or more, and their displacements attain as great a vertical throw as $2\frac{1}{2}$ miles.

Dutton observed that there had been successive movements on or near the same plane at widely separated geologic periods. Noble¹ describes in detail the evidence of repeated movements in the case of the West Kaibab fault, which is "laid open to study for a vertical mile" in the Muav-Flint canyon. Three separate displacements are observed. The lowest and oldest traverses the pre-Cambrian formations, bringing the Unkar strata down into contact with the much older Vishnu schists. The edges

¹ NOBLE, L. F., The Shinumo Quadrangle, Grand Canyon District, Arizona, U. S. Geol. Surv., *Bull.* 549, p. 75, 1914.

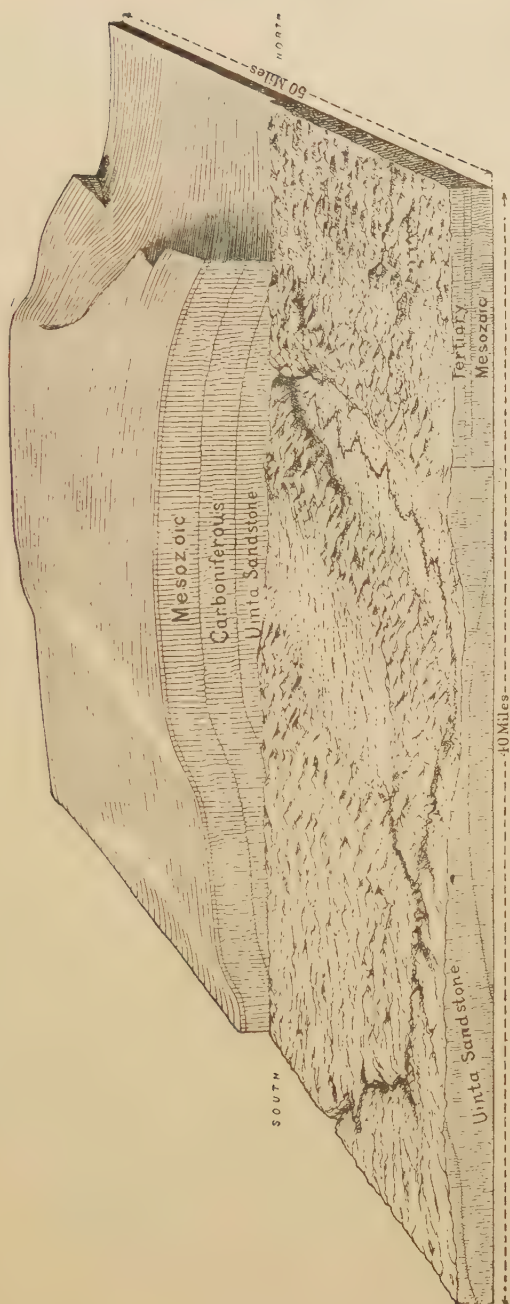


Fig. 54.—Bird's-eye view of the Uinta mountains, illustrating the relation of normal faults to broad uplifts. (After Powell.) The block in the foreground exhibits the present surface; the block in the background is represented as it would stand had there been no degradation. The fault shown in the foreground is a continuation of the fault shown in the background. The course of the Green River through Brown's park and the Canyon of Codorie is seen in the front block. The summit of the restored block is the last bed laid down before the inception of the upheaval. The vertical and horizontal scales are the same.

of the Unkar beds are dragged sharply up against the Vishnu and the plane of crushing of one wedge against the other is marked by cemented breccia or by a soft talcose selvage. This fault is truncated by the base-leveled surface of erosion which underlies the basal Cambrian sandstone. The movement was, therefore, pre-Paleozoic. Later displacements in the same zone traverse the Paleozoic and comprise a marked flexure and a later normal fault. According to Noble the more massive strata bend down in the flexure in one graceful arc, whereas the softer ones are crumpled. The throw of the fault attains as much as 2,000 feet. Noble comments:

The flexure probably originated when the Paleozoic rocks were buried under a considerable load of Mesozoic strata, for the thick and massive beds yielded by bending rather than by breaking. This movement must have occurred not long after erosion began in the region and therefore early in Tertiary time. The fault that breaks the flexure may have occurred at any time after the greater part of the mass of the Mesozoic strata had been eroded away.

The displacement on any normal fault varies from zero to a maximum for that particular fault. The maximum displacement may have occurred near one end or toward the middle of the length of the fault. At the zero point the fault ceases to exist and may pass into a monoclinical flexure or into undisturbed flat strata. Furthermore, beyond the zero point the displacement may reappear, with the downthrow on the same or even on the opposite side of the fracture. Thus, if a fault trends north and south and the downthrow in one section be the eastern block, the movement beyond an interval of no displacement may be in the same sense, downthrown to the east, or may be in the opposite sense, downthrown to the west. Dutton describes cases of this latter type, where the fault continues, but with reversed displacement, in the Sevier and Thousand Lake faults of the High Plateaus.¹ The effect of the movements in such a case is the same as if the two blocks on either side of the fracture had rotated in opposite directions around an axis which crosses the line of the fault at the point of zero displacement.

The possible combinations of normal faults are many, but certain types are distinguished because of their striking effects

¹DUTTON, C. E., *Geol. of the High Plateaus*, U. S. Geog. and Geol. Survey of the Rocky Mt. Region, chap. II, pp. 31 and 33.

at the surface. One such structure is known as a *step fault*. It consists of several normal faults, which are parallel among themselves and are downthrown in the same direction. The effect is that of a flight of steps. It is of common occurrence in fault scarps of great throw and reduces the apparent angle of dip of the fault, considered as a single scarp, to a slope that may be too gentle to suggest the faulted character of the declivity.

Step faulting is a feature of rotated mountain blocks and results from the disturbance of stability incident to the rotation of the block. It may occur on the steep fault scarp, as has been suggested in the preceding paragraph, or on the gentler tilted slope. For instance, the Sierra Nevada of California faces the Basin region of Nevada with a slope which, though steep, is usually not greater than the angle of rest of loose rock. It is nevertheless a fault scarp, but one which is modified by normal step faulting in such a manner that it simulates a steep erosion slope.

Another combination of high-angle faults, which is commonly attributed to normal displacements, is the *trough fault*. A trough fault is that kind of structure in which a long, narrow strip of the earth's surface has either sunk deeper or has not been raised as high as the masses on either side of it. The sides of the strip are high-angle faults, which are frequently nearly vertical, and which may be interpreted either as normal or upthrust. Either one or both of the two single faults may be replaced by step faults. The effect is to produce a dropped wedge, where the faulting occurs beneath the surface, or to form a trough of which the fault scarps are the sides, where the surface is displaced.

The German term "*Graben*" is in general use to designate valleys which are formed by trough faulting. The name *rift valley* is the English equivalent.

It is at present a question on which opinion is divided whether rift valleys are effects of normal or of upthrust faulting, and rather far-reaching inferences are drawn as to the extension or compression of large segments of the earth's crust, according to the interpretation adopted. The idea of normal faults is the older, and it passed unchallenged until a better understanding was obtained of great upthrusts. The traditional view is now, however, doubtful, and a conclusion either way can be safely stated only when there is definite evidence of either normal or thrust faulting.

A sunken wedge is described by Noble as part of a mass of pre-Cambrian strata exposed in the depths of the Grand Canyon (Fig. 55). It is part of a greatly faulted block which was displaced in pre-Cambrian time and which consists of minor

blocks and wedges of all sizes, ranging from those included between the larger faults down to those formed by the innumerable faults of small throw. . . . Every detail of the wedge is revealed from its summit, where it is truncated by the pre-Tonto unconformity down to its apex, a vertical distance of 1,000 feet. Where the fault planes traverse the harder strata they are characterized by fault breccia and slickensided surfaces.¹

The crushing indicated by the breccia and slickensides appears to be developed on a scale greater than can reasonably be attributed to the sinking down of the wedge under its own weight. If we attribute the effects to vertical displacement we must assume that the movement involved much larger masses, whose superincumbent weight bore upon this block and its surroundings. This was probably the case. It is wise, however, to bear in mind that the displacement may have had a horizontal component of greater or less proportion and the dropping of the wedge may be one result of local widening of the fault fissure due to horizontal displacement parallel to the fault strike, under general compressive strain.

The Rheingraben, or fault trough of the Rhine Valley, is a very characteristic example of trough faulting on a large scale. The Rhine flows northward across the summit of the plateau of northwestern Europe. A part of the course is in a canyon, which the river has carved as an antecedent stream. But before entering the canyon, the Rhine flows for 170 miles in a broad depression which is not an effect of erosion. The river follows a trough produced by faulting. The accompanying section (Fig. 56) reproduced from Kober,² shows how the Tertiary formations have been inlaid between masses of Triassic, Permian, and older rocks, as if by the dropping down of several wedges. The interpretation admits of no alternative provided the faults extend as drawn, converging in depth. But if it be recognized that that is an assumption, an alternative may be admitted. It is shown in the

¹ NOBLE, L. F., The Shinumo Quadrangle, Grand Canyon District, Arizona, U. S. Geol. Surv., *Bull.* 549, p. 77 and plate 25B, 1914.

KOBER, LEOPOLD, "Der Bau der Erde," p. 52. Berlin, 1921.



FIG. 55.—Faults in the Unkar Wedge in the Canyon of Shinumo Creek, Grand Canyon of Arizona. The wedge outline is 1,000 feet from bottom to top. Drawn from photograph. (After Noble in U. S. Geological Survey, *Bull.* 549.)

supplementary figure which is drawn to the same scale as that of Kober, but with the faults diverging downward.

If the Rheingraben is a result of normal faulting, the uplifting force which raised the plateau acted primarily in a vertical direction and, as the arch rose and the strata were extended, the wedges sank to the amount required to fill the space. On the other hand, if the Rheingraben is due to reverse faulting, the pressure acted in a horizontal direction and the arch is an effect of compression. The facts are indeterminate (Fig. 56).

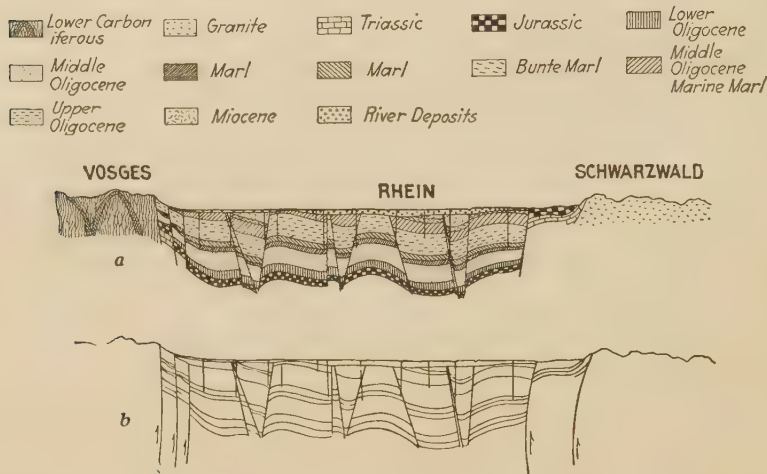


FIG. 56—*a*. Profile through the Middle Rhein Valley to the north of Muhlhausen in Alsace. The structure of the low-lying Rhein-valley block between the Vosges and the Schwarzwald, from borings. The strata in general belong to the Middle Oligocene and later periods, lying on the Upper Dogger. (From Tornquist, "Formationskunde," elaborated by W. Wagner. After Kober, "Der Bau der Erde," 1921.)

b. The same, as interpreted if due to compression.

In Palestine, Arabia, and eastern Africa there are trough faults of remarkable extent, comprising the Jordan valley, the Dead Sea and Gulf of Akaba, the Red Sea, and the great "Rift valley" of eastern Africa. The Jordan-Akaba depression, as it may be called from its two extremities, is the best-known and possibly the most remarkable trough in the world. It is 400 miles long, from its head where the waters of the Jordan gather to form the main river to Cape Ras Mohammed where it enters the Red Sea.

It is 15 to 20 miles wide between plateau margins, and in the deepest part it descends to 2,600 feet below the Mediterranean. The level of the water of the Dead Sea is 1,292 feet below the Mediterranean and the water is 1,308 feet at the deepest sounding. Referred to the plateaus on either side, the bottom of the trough reaches a maximum of 5,193 feet below Jerusalem and 5,243 below Mt. Nebo.¹ It thus lies like a sunken keystone between two elevated buttresses of equal height. The suggestion that it is due to the apparent sinking in of the keystone is very obvious, but opinion is by no means agreed that such is the case, and there is much evidence to indicate that even this great depression may be an effect of the forces of compression, from which the associated structures evidently resulted.

The geology of the Jordan-Akaba trough was described by Hull² and by Lartet,³ both of whom give sections across it. A high-angle fault is shown as occurring along the eastern side of the trough. If it dips to the west far below the surface, as it appears to where it is visible, the displacement could only have occurred during an epoch of extension of the zone, following the up-arching of the strata. The assumption is not uncommonly made that that was the sequence of events. If, on the other hand, the fault curves back under the eastern plateau, the movement was one of upthrusting consistent with and presumably contemporaneous with the process of folding. Kober⁴ describes the region, including the northern end of the Red Sea and the Lebanon Range, as a typical folded zone.

The Jordan-Akaba depression occupies the summit of the plateaus of Palestine and ends in the Red Sea. The Red Sea similarly extends along the highest part of the plateau that forms western Arabia and eastern Egypt. From the southeastern end of the Red Sea there branches off to the southwest, across the plateau of Abyssinia and Somaliland, a valley not so deep as but bounded by cliffs like the valley of the Dead Sea. It ends in Lake Rudolf, a salt lake in Kenya Colony or German East Africa, that was. West of Lake Rudolf and distant 340 miles is the northern end of the Great Rift Valley, which extends in a long curve

¹ *London Times Atlas*, Plates 51 and 52, 1922.

² HULL, EDWARD, "The Survey of Western Palestine," 1886.

³ LARTET, LOUIS, "Exploration de la Mer Morte," etc., 1877.

⁴ KOBER, L., "Der Bau der Erde," p. 85, 1921.

southwest, south, and southeast, 1,500 miles to the coast near Beira. It lies along the western side of the high plateau of East Africa for half its length and then crosses it to its eastern scarp. Suess¹ first called attention to this remarkable series of depressions, which are evidently related to the uplift of the plateaus they traverse and which constitute the equivalent of a great mountain system. Gregory² has contributed the most comprehensive description of their features and has discussed their relation to other great features of the world.

The following statements are condensed from his description in *The Geographical Journal*:

Different portions of the Rift System, as the whole may be called, present different aspects. The Jordan-Akaba fault trough has been described. The Gulf of Suez and the Red Sea are regarded by some as following a faulted zone and by others as being a down fold. The evidence is apparently not conclusive. Of the section across Abyssinia to Lake Rudolf,—Gregory, who inclines decidedly toward the recognition of faults, says:

The walls are irregular, owing to projecting spurs, to breaches cut by rivers, and to smothering piles ejected by volcanoes. In spite of . . . interruptions . . . the continuity of the Rift Valley is maintained. The walls are usually scarp-like. Their continuity and the trench-like form of the valley are clearly shown on maps, and the abrupt edge of the plateau and precipitous nature of the walls are described by many travelers.

South of Lake Rudolf the valley is broken, by ridges and steps, into closed basins, extending to Lake Magadi. The intervening ridges are made up of volcanic material and the floor of the valley is studded by volcanoes, some only dormant, others in the last stages of decay. Gregory discusses a succession of valleys, by which the Rift may be traced to Lake Nyasa and so to the coast near Beira. There is, however, some question as to the continuity of the structure between Lakes Magadi and Nyasa, as the rift features are not clearly marked.

That portion of the Rift which has just been traced from Abyssinia to the southeast coast of Africa traverses the highest

¹ SUESS, EDUARD, "Das Antlitz der Erde," vol. 1.

² GREGORY, J. W., "The Great Rift Valley," 1896.

Ibid. The African Rift Valleys, *The Geographical Journal*, vol. LVI, July, 1920.

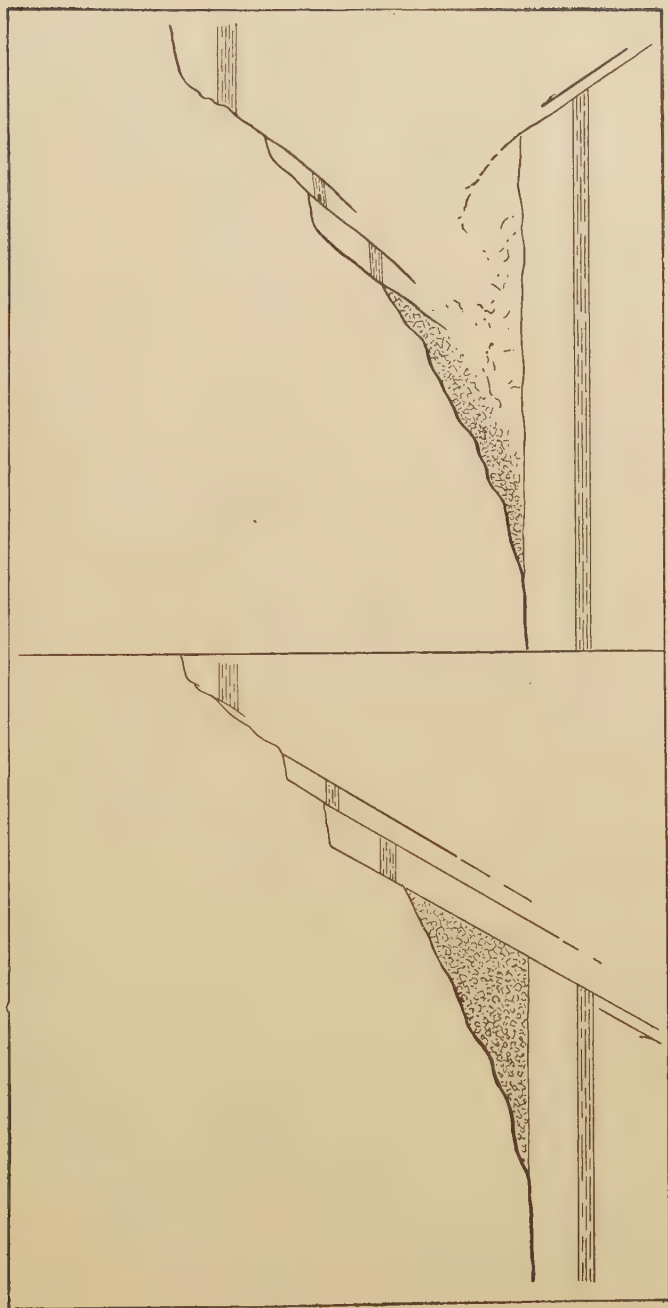


FIG. 57.—Sections of the Albert Nyanza Rift valley. (After Wayland.)

(a).—Interpretation of the valley as a dropped block bounded by normal faults. (After Gregory.)

(b).—Interpretation of the valley as an effect of upthrust from either side, according to Wayland, the normal faulting being a subordinate feature.

zone of the eastern part of the African plateau. West of it is a depression in which lies Lake Victoria Nyanza, whose generally rounded form and irregular shores contrast strongly with the features of the long, narrow, steep sided lakes which occupy the great western rift valley. They are Lakes Albert, Edward, Kivu, and Tanganyika. They form the great arc which traverses the western summit of the plateau region, and which is 1,500 miles long. Tanganyika, the greatest lake of the system, is 4,190 feet deep and its floor lies 1,664 feet below sea level. The trough is bounded by high walls which are continuous, except where they have been breached by intersecting fault valleys or by a few inflowing rivers. The drainage as a whole is away from the lake. The Albert Nyanza, at the northern end of the chain of lakes, is described as bounded on the east by a precipitous bank 1,000 to 1,500 feet high, while the western shore is formed by a chain of lofty mountains, the highest peaks of which are said to rise 8,000 feet above the level of the lake. The mountain scarps are compared to walls resembling those of a fiord in Norway.

It was at one time suggested that the great rift valleys were effects of erosion, but there is now no question but that they are due to faulting. There are, however, differences of opinion as to whether the major faults are normal and therefore indicate tension, or are reversed and express compression. Gregory is the champion of the tension theory, whereas the compression theory has recently been put forward by Wayland.¹ The accompanying diagrams (Fig. 57) are taken from the latter's paper. It is not the purpose in this description of great high-angle faults to discuss the origin of the rift features. It may be noted, however, that the three great examples which have been cited, namely the Valley of the Rhine, the Jordan-Akaba Trough, and the great Rift Valley of Eastern Africa, are all of them similarly situated in the summits of plateaus and may be explained, either as effects of collapse after a preceding up-arching of the surface, or as depressed strips which have been overridden by segments of the plateau pushed up from either side. The mere fact of the existence of a graben, bounded by steep fault scarps which exhibit normal faults equivalent to land slides, is not in itself demonstrative evidence either of tension or compression.

¹ WAYLAND, E. J., Some Account of the Geology of the Lake Albert Rift Valley. *Geog. Jour.*, vol. LVIII, pp. 344-359, 1921.

Some Low-angle Faults.—In the Northwest Highlands of Scotland there is an abnormal relation of gneisses and sedimentary rocks which long puzzled the ablest geologists and led to the suggestion of various erroneous interpretations. Finally, Messrs. Peach and Horne¹ recognized that the gneisses, which seemed to lie conformably upon the sedimentary rocks, had in fact been pushed or thrust over upon them. The structure, which is described in a subsequent section (page 92), is a very complex one, but the fact that the gneisses are overthrust is now clearly

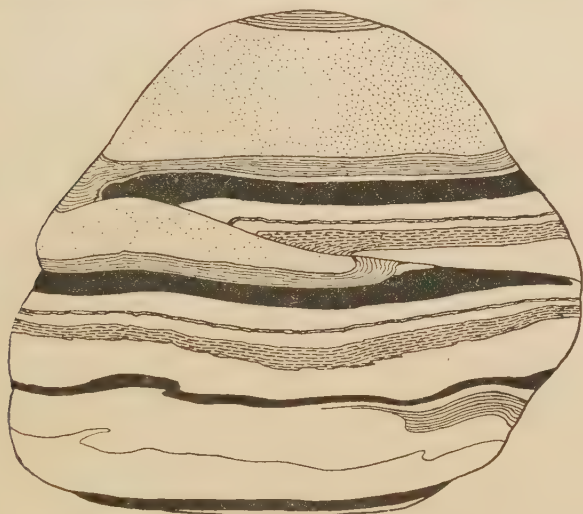


FIG. 58.—Illustration of a low-angle thrust. (Drawn from a pebble in the Stanford collection.) The bedded strata of the original rock were bent and sheared by the overthrust which traverses the middle of the pebble. The pebble was subsequently worn from a fragment of the rock, but it did not part on the thrust plane. About three times natural size.

recognized and the fault upon which the movement occurred is called a *thrust plane*.

The term *thrust* has since come into general use to replace the less expressive phrase reverse fault. Any reverse fault is a thrust.

The concept, which is thus illustrated, is characterized mechanically by the fact that one mass of strata has been pushed over

¹ PEACH, B. N. and HORNE, JOHN, Report on the Geology of Northwest Sutherland. *Nature*, vol. XXXI, pp. 31-35, Nov., 1884.

upon an adjacent mass, usually in such a manner that older strata come to rest upon younger strata along the plane of dislocation. A thrust has the character of all reverse faults in that the fault plane dips under (or *hades* toward) the upthrow. Thus a thrust involves a shortening of the strata which are dislocated, and is attributed to a compressive stress.

The first discovery of a thrust was made in 1826 by Weiss, a German geologist, who in the vicinity of Dresden observed that an ancient granite lay flat upon Cretaceous strata in a position which he recognized as due to an overthrust movement.¹ His explanation was, however, met with incredulity by the then masters of the science. Yet eleven years before Sir James Hall had correctly described folds produced by compression, and it seems, in the light of our present knowledge, an obvious inference that overthrusts result from the same action.

H. D. and W. B. Rogers were the first to connect overthrusts with folds. In their investigations of the structure of the Appalachians they found that "inverted flexures frequently pass into faults," which invariably arose along the northwest side of an anticlinal axis and like the axes of the folds maintained a remarkable parallelism.²

The observations of the Rogers brothers were made chiefly in Pennsylvania and Virginia. Safford observed in Tennessee thrusts of a similar but more pronounced character, associated with less developed folds. Describing a section across the most closely compressed portion of the valley of Tennessee, he wrote:

The length of the section is 52 miles. Eight great faults are crossed. . . . It is to be observed that no great flexures occur. . . . The incipient folds were split open longitudinally and the southeast side of each was heaved up and over the northwestern.³

The unequal development of folds and thrusts in the Virginia, Pennsylvania and Tennessee sections of the Appalachian Valley

¹ ROTHPLETZ, A., *Die Ueberschiebungen und ihre methodische Erforschung. Compt. Rend. International Geological Congress, Zurich*, p. 252, 1894.

² ROGERS, H. D. and W. B., *On the Physical Structure of the Appalachian Chain, as exemplifying the laws which have regulated the elevation of great mountain chains generally. British Assn. Reports*, vol. 12, Trans. of Sec's, pp. 40-42, 1842. *Am. Jour. Sci.*, vol. 44, pp. 359-365, 1843.

³ SAFFORD, JAMES M., "Geology of Tennessee," pp. 189-190, 1869.

was subsequently explained as a result of the difference of load resting on more or less deeply buried strata. In each section the controlling stratum was a very thick limestone, which under less load broke (Fig. 60) and was overthrust at an earlier stage of development of the folding than where it was more heavily loaded.¹



FIG. 59.—A pebble of sandstone, traversed by two quartz veins, one of which is displaced by a reverse fault or thrust, *TT*, which also extends through the sandstone.

McConnell,² describing a section of the Rocky Mountains near the fifty-first parallel, in 1886, quoted Safford and drew a

¹ WILLIS, BAILEY, *Mechanics of Appalachian Structure*. U. S. Geol. Surv., *Thirteenth Ann. Rept.*, pp. 226-230, 1890.

² MCCONNELL, R. G., *Report on the Geologic Structure of a Portion of the Rocky Mountains*. G. & N. H. Surv. of Canada, *Report*, part D, p. 31, 1886.

comparison between the structures he had observed in Tennessee and those of the Rockies. Regarding the latter he says:

In the section examined there are seven principal faults, besides some of minor importance, and six well-defined blocks, the latter resting on one another in regular succession from west to east. . . . Overturned folds were observed along the course of some of the faults, but they are usually small and of minor importance as a structural feature.

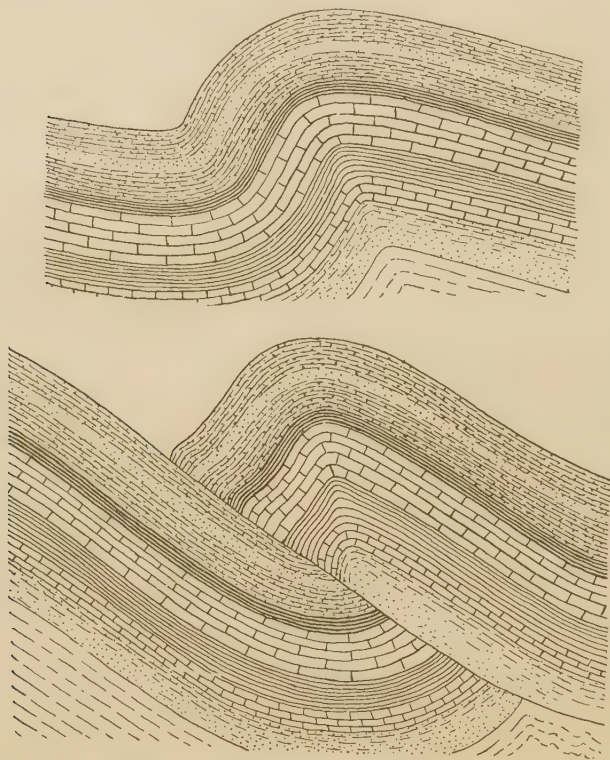


FIG. 60.—Development of a thrust of the Appalachian type, a break thrust.

Thus it became evident that overthrusts might develop in incipient as well as in more complete folds. The work of Peach and Horne in northwest Scotland, already quoted, went even further and showed that great thrusts might originate without previous folding as a result of shearing and displacement on the shearing planes. Such folds as occur in connection with thrusts

of this character are effects of the thrusting, not of conditions giving rise to it.

Keith,¹ who after years of investigation worked out the complex structure of the Smokey Mountains of North Carolina, found there great shear planes, overthrusts, which antedated the folding and are themselves folded in anticlines and synclines. In this case, as in the Highlands of Scotland, the shearing had originated in gneisses and granites deep beneath the horizon of stratified rocks and had no relation to any folds, except those which were induced in strata in the line of the displacement.

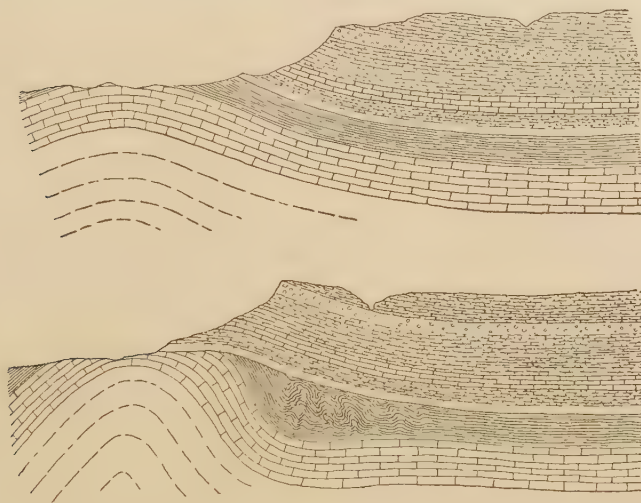


FIG. 61.—Development of an erosion thrust of the southern Appalachian type. (After Hayes.)

Overthrusts, originating either deep beneath the zone in which strata can fold or in the zone of folding, may extend to the surface and there produce remarkable conditions of superposition. Effects of this character were first observed by Russell in Georgia, in the southern extension of the Appalachian faulting, and were correctly interpreted by Hayes. The older strata (Cambrian) were found to rest apparently without disturbance upon younger (Carboniferous) over large areas. The Cambrian lies in synclines

¹ KEITH, ARTHUR, Roan Mountain Folio. U. S. Geol. Surv., *Geologic Atlas*, No. 151, text and structure sections.

seemingly conformably, on an eroded surface of the Carboniferous. Hayes¹ explained this anomalous condition by assuming that in an adjacent section erosion had removed the crest of a slight fold in such a manner as to expose the edge of a rigid stratum, and the latter, meeting with no resistance, rode forward on the eroded plain. (Fig. 61.)

Willis² later applied Hayes' interpretation to the Lewis overthrust, which underlies the Rocky Mountains where they are crossed by the 49th parallel, it being evident that the mountain mass, consisting of very old strata, had been pushed forward on the eroded surface of the Great Plains so as to overlie much younger strata for a distance of seven miles.

Overthrusts have since been recognized as a common, if not general, type of displacement along the eastern edge of the Rocky Mountains, as well as in the interior of the system.³

In the Coast Ranges of California overthrusts are found as a subordinate structure, developed in connection with the dominant upthrusts of that region. Recent work both at Stanford and at the University of California has greatly modified the concepts formerly entertained in regard to the structure, but as yet very little has been published.

Low-angle thrusts or overthrusts are thus recognized as of general occurrence in the compressed mountain chains of North America. They are similarly developed in Europe. Reference has already been made to the great displacements of this character in Scotland. The Cretaceous chalk formations of southern England, which appear to be but little disturbed, are traversed by extensive thrusts.⁴ A long and intense thrust, associated with

¹ HAYES, C. W. Overthrust Faults of the Southern Appalachians. *Bull. G. S. A.*, vol. 2, pp. 141-152, 1891.

² WILLIS, BAILEY, Stratigraphy and Structure of the Lewis and Livingston Ranges, Montana. *Bull., G. S. A.*, vol. 13, pp. 305-352, 1902.

³ BLACKWELDER, E., Geology of the Wasatch Mountains, Utah. *Bull., G. S. A.*, vol. 21, pp. 517-542, 1910.

RICHARDS, R. W., and MANSFIELD, G. R., The Bannock Overthrust, Idaho. *Jour. Geol.*, vol. 20, pp. 681-709, 1912.

ZIEGLER, V., Foothills Structure in the Rocky Mountains. *Jour. Geol.*, vol. 26, pp. 715-740, 1917.

DAKE, C. L., The Hart Mountain Overthrust, Wyoming. *Jour. Geol.*, vol. 26, pp. 45-55, 1918.

⁴ STRANAHAN, A., Thrusts in English Chalk. *Quart. Jour. Geol. Soc.*, LI, p. 549, 1895. Geology of the Isle of Purbeck, *Memoirs of the Geological Survey*.

close folding, forms the southern limit of the coal fields of northern France and Belgium, the Devonian being thrust over upon the Carboniferous, which is overfolded on itself.

In the Alps and Pyrenees thrusts of an unusual type are associated with very large recumbent folds, constituting structures which are the most complex known to geologists. Arnold von der Escher, Albrecht Heim, Rothpletz, Marcel Bertrand, Killian, and Lugeon are among the geologists whose patient labors have assembled a mass of information regarding the complexities of



FIG. 62.—Perspective view and section of a thrust of the type common in Eastern Tennessee, a variety of the Appalachian thrusts.

these structures. The facts of the visible relations have been worked out in great detail. The correct interpretation of the mechanics of uplift still awaits discovery, nevertheless. The present solution, offered by Lugeon in 1903 and generally accepted, defies the laws of mechanics of materials in that it requires that mountain masses have been piled on each other to impossible heights. It will, no doubt, eventually be modified. It is probable that the conditions will then be found to be of the same general character as those which characterize the Highland structures and other similarly complex mountain ranges.



FIG. 63.—An over-thrust in the Alps. Section through the Glarner "double fold," as originally drawn by Heim; subsequently interpreted as an overthrust by Rothpletz; and since regarded as a part of the great "Decken," or "nappes," of which the Alps are supposed to consist.

Length of section about 15 miles. (After Heim. "Mech. der Gebirgsbildung.") Profile XIII. Plate VII.

Low-angle overthrusts are thus known in all compressed mountain chains of Europe and North America. They occur in the Himalayas and in China. They are, in fact, as commonly developed as folds and are to be regarded as a normal result of the displacements of larger or smaller sections of the earth's crust.

Underthrusts also occur. They do not differ from overthrusts except that they appear to have an opposite relation to the active force, if the force of compression be supposed to have been exerted from one direction only. The moving mass then appears to have been thrust under the passive in the case of an underthrust.

The preceding review of the occurrences of low-angle thrusts shows that they always result from compression, but may arise from a variety of mechanical conditions. It was first recognized that an overthrust might develop in the overturned limb of a fold. Such a structure then pertains to the phenomena of folding and originates in that zone of the Earth's crust where folding is the initial effect of compression. Later it was found that great thrusts are shearing planes and folding is only a subordinate feature of the structure. Shearing, however, is a mechanical effect which results from compression of a massive rock, like granite, or of schists too

deeply buried to fold. Thrusts of this type, which includes some of the greatest displacements known, thus have a deeper origin than those which arise from folds. It is probable that the deepest and greatest displacements are of the shearing class. The facts which indicate their existence in the profound depths which are beyond our observation are so cogent and the apparent horizontal movements are so great that Gilbert, and subsequently Barrell, with reason postulated a "zone of mobility" beneath the rigid crust.

Having recognized that a segment of the crust may be displaced with a forward and upward movement, i.e., may be overthrust, it is obvious that the front edge of the mass may emerge at the surface and may be pushed over a plain. Meeting with no resistance, the mass would advance like a glacier. Such a thrust is the superficial expression of one originating in a fold or it may be in the deeper zone of shearing.

Chamberlin and Miller have conducted experiments on low-angle faulting, and determined the theoretical conditions controlling their origin.¹

Low-angle faults of normal displacement are not of common occurrence. The normal fault being an effect of gravity tends to have a large vertical component of slip, whereas a low-angle fault has but a small component in that direction. The conditions are therefore not favorable to normal displacements where low-angle faulting is developed. Nevertheless, normal faults do pass into low-angle faults in consequence of the curvature of the fault surface. This change of attitude is characteristic of landslides, which start with a steep surface of dislocation, but are diverted into a nearly or quite horizontal position by the resistance of the terrain down which they slide. We observe this effect in all those superficial accidents that we call landslides. When the displaced masses attain great size, we change our terms and call the thing a fault because we cannot see the lower end of it. It is, however, reasonably probable that even the great normal faults along the continental margins, descending beneath the sub-oceanic masses, curve outward and become low-angle faults.

A low-angle normal fault thus shows an analogy with a high-angle thrust fault. Thrust faults commonly originate at a low

¹ CHAMBERLIN, R. T. and MILLER, W. Z., Low-angle Faulting. *Jour. Geol.*, vol. 26, pp. 1-44, 1918.

inclination, but may, if they meet with resistance, be diverted to a steep or vertical attitude. They then appear at the surface as upthrusts. Normal faults similarly depart from their original verticality and approach horizontality on encountering immovable underlying masses.

Highland Structure.—Thrust faulting on a great scale, with or without folding but with folding a subordinate feature where it does occur, characterizes a remarkable region in the Northwest Highlands of Scotland and having been first recognized in that region has become known as "Highland Structure."

The Northwest Highlands had, through the researches of many of Great Britain's foremost geologists, including Murchison, long been the scene of controversy, when Messrs. Peach and Horne made it classic ground by their penetrating and decisive investigations, which established beyond question the existence of a type of structure previously unknown and in the light of the then existing knowledge of earth-dynamics inconceivable. The history of investigation from 1814 to 1900 is summarized in Chapter 2 of the Memoir published in 1907.¹ In the course of the many and detailed studies of the rocks and their succession made during nearly a century the thrusts had been regarded as unconformities, and theories had been evolved to account for the metamorphism of apparently younger, overlying strata where underlying strata are not altered; the fact being that the overlying are older than the underlying, upon which they are overthrust. (Figs. 64, 65 and 66.)

Horne thus summarizes the description of the structures:²

1. By lateral compression of the earth's crust the rocks have been thrown into a series of folds, usually inverted, accompanied by several faults or thrusts. The general strike of these folds and dislocations is from N.N.E. to S.S.W. The axial planes of the folds, the reversed faults, and the component beds dip, as a rule, in one direction towards the E.S.E. In the middle limb of the overfold the constituent particles are attenuated, and along that limb, the overfold may or may not pass into a reversed fault.

¹ The Geological Structure of the Northwest Highlands of Scotland, by B. N. PEACH, JOHN HORNE, and others, edited by S. R. ARCHIBALD GEIKIE, *Memoirs of the Geological Survey of Great Britain*, 1907.

² *Ibid.*, pp. 463-464.

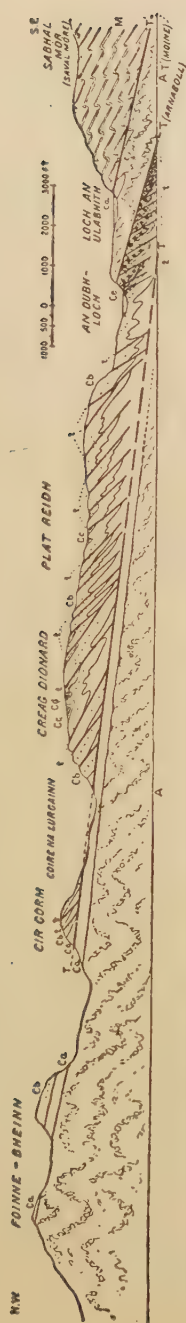


FIG. 64.—Highland structure. Section from Foinne-Bheinn by the Plat Reidh and An Dubh-Loch to Sabhal Mòr, showing the basal quartzite of the Cambrian resting unconformably on the Lewisian Gneiss and itself overridden by higher members of the Cambrian series which have been pushed from S.E. to N.W. on a major thrust and piled up by successive minor thrusts. On the right of the section the Lewisian Gneiss and the Eastern Schists are shown overthrust upon the Cambrian.

A. Lewisian Gneiss. Ca. Basal Quartzite (Cambrian). Cb. Pipe-rock. Cc. Fucoid-beds. Cd. Serpulite-grit. Ce. Limestone. M. Eastern Schists. T. Thrusts. T'. Moine thrust. t. Minor-thrusts.

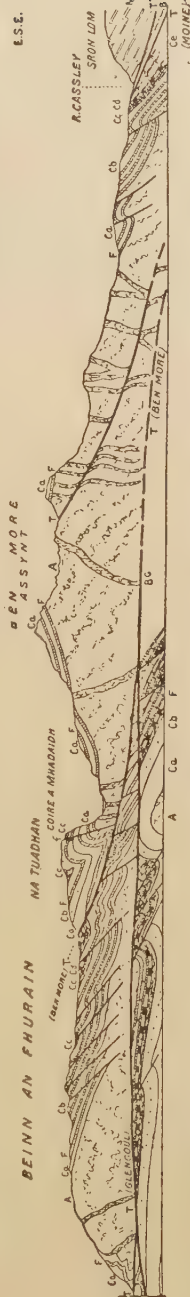


FIG. 65.—Highland Structure. Section from Beinn Gharbh by Choc an Droighinn, Beinn an Fhurain, and Ben More, Assynt, to the River Cassley, showing the pre-Cambrian (Lewisian) Gneiss overthrust upon the Cambrian and the latter piled up by numerous minor thrusts.

A. Lewisian Gneiss. B^c. Dykes in Gneiss. B. Torridon Sandstone. Ca. Basal Quartzite (Cambrian). Cb. Pipe-rock. Cc. Fucoid-beds. Cd. Serpulite-grits. Ce. Limestone. Ce I. Limestone (Ghrudaigh group). Ce II. Limestone (Eilean Dubh group). F. Intrusive Igneous Rocks. M. Eastern Schists. T. Thrusts. T'. Moine thrust. f. Faults.

2. Without incipient folding, the strata are repeated by a series of minor thrusts or reversed faults, which lie at an oblique angle to more important dislocations, termed by us major thrust planes. They are likewise inclined to the E.S.E., the direction from which the pressure proceeded.

3. By means of major thrusts of varying magnitude, striking generally N.N.E. and S.S.W., the following structures have been produced: (a) certain subdivisions of the Cambrian system have been heaped up and driven westwards along planes produced in underlying undisturbed materials; (b) masses of Lewisian gneiss with its unconformable covering of Torridon sandstone and Cambrian strata override the piled up strata beneath; (c) the Eastern schists have been thrust far to the West till, in some instances, they rest directly on undisturbed Cambrian rocks.

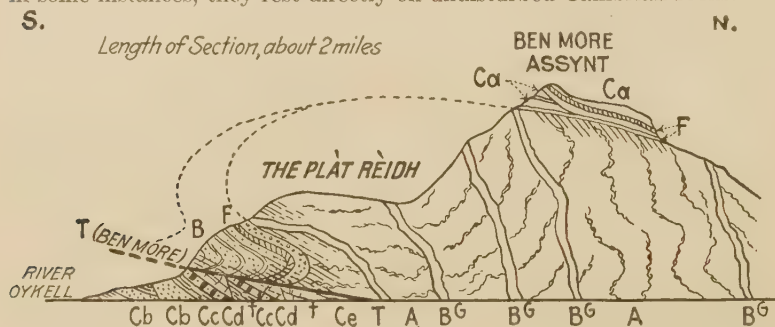


FIG. 66. Highland structure. Showing an overturned fold in sedimentary beds enveloping a gneissic core. Section from the Oykell Valley across the Plat Reidh and Ben More, Assynt.

A. Lewisian Gneiss. B^G . Dykes in Gneiss. B. Torridon Sandstone. Ca. Basal Quartzite (Cambrian). Cb. Pipe-rock. Cc. Fucoid-beds. Cd. Serpulite-grit. Ce. Limestone. F. Intrusive Igneous Rocks. T. Ben More thrust. t. Minor thrusts.

4. Owing to the travelling of the rocks from East to West and also to the friction along the unyielding lower plane or "sole" of the thrust, there was a tendency in the materials to fold over and curve under, thus producing inversion.

5. While the planes of the major thrusts, along which the materials have been driven, usually dip at low angles to the E.S.E., yet they are frequently irregular both in direction and angle of inclination.

6. The outcrops of the major thrust-planes resemble boundary lines between unconformable formations because (1) there is always a complete discordance between the strata lying above and below the planes of disruption, and (2) each successive thrust may be overlapped in turn by a higher one.

7. Thrusts of smaller magnitude, when followed along the strike, may merge into folds.

8. By means of denudation, outliers of the materials lying above the planes of disruption have been formed, . . . the upper discordant members being separated from the lower by a fault with a circular outcrop.

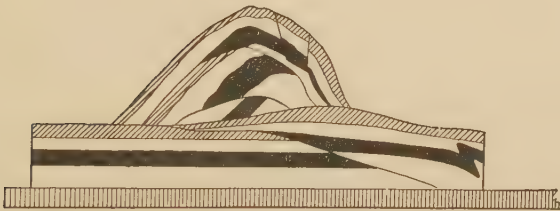
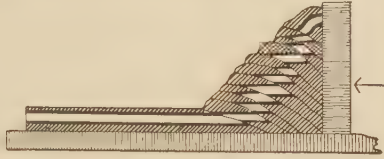


FIG. 67.—Illustrations of Highland structure. Experimental results illustrating the development of major and minor thrusts by pressure applied to beds of sand. (After Cadell.) The mechanical displacements occur along shearing planes, which develop from left to right, retrogressively, in consequence of piling up of the material in front.

9. The more powerful displacements were accompanied by differential movements of the materials which resulted in the development of new structures.

The correct interpretation of the complex structure of the Scottish Highlands, after three-quarters of a century of study,

was justly regarded as an achievement which reflected great credit on the two geologists, Peach and Horne, to whom it was chiefly due, and also as a discovery of a unique type of structure. It is unique, however, only because it was the first of its kind to be described. The mechanical conditions which gave rise to the great major thrusts and their associated minor thrusts and overfolds are probably not peculiar to this particular segment of the earth's crust, and similar effects of deformation may be expected to occur in other mountain ranges. The Highland type of structure is a specific example of a general effect.

Geometric Classification of Faults.—A fault, although part of a curved surface and having some thickness, may be regarded as a plane over any small area and so also may the surfaces of the strata which it cuts be treated as planes. Hence the geometry of faults and of the segments of strata displaced by them is the geometry of intersecting planes.

Planes intersect in lines, which are called traces. A fault plane cuts a stratum or a vein in a straight line which is the trace of the fault with the stratum, or vice-versa. Since the stratum is displaced by the fault plane, there are two intersections or traces of the fault with the stratum and the distance between the traces is the apparent displacement of the fault.

We express the attitude of any plane, whether fault or stratum or vein, by its strike and dip, which are defined on page 9. And it follows that if we know the relation of the strike and dip of a fault in relation to the strike and dip of the strata, we can express the relation of the two planes to each other. In order to use these relations to establish a geometric classification of faults, the strike of the fault is taken as its principal character, and its position with reference to the strike and dip of the strata determines the class of the displacement.

In the course of fieldwork we first observe the geometric relations of the fault to the strata and thence determine the type of the fault. There are four principal types, which are distinguished as follows:

- (1) Strike and dip of the fault are both parallel to the strike and dip of the strata—*a bedding fault*.
- (2) Strike of the fault is parallel to, or nearly parallel to, the strike of the strata, but the dip of the fault cuts across the dip of the strata—*a strike fault*.

- (3) Strike of the fault is perpendicular to, or nearly perpendicular to, the strike of the strata—a *dip fault*.
- (4) Strike of the fault is oblique, forms a distinct acute angle with the strike of the strata—an *oblique fault*.

In a bedding fault the plane of movement is the bedding plane of the strata. The displacement may be in any direction whatever. It is not shown by the strata, which retain their continuity and parallelism, but may be detected by striations, by slickens, by offset joints or dykes, or by pinches and swellings.

Strike faults cause a repetition of strata, or a gap, in cross-section, according to the way in which the dip of the fault cuts across the dip of the strata and according to the normal or reverse character of the fault.

Dip faults cut off the strata across their strike and offset them to one side or the other. The obvious displacement is a horizontal one, but it may be occasioned by a vertical movement across inclined beds.

Oblique faults approximate the effects of strike faults or of dip faults, according as they strike more nearly parallel with the strike of the strata or perpendicular to it.

Any of these four types of faults—bedding, strike, dip, or oblique faults—may be either normal or reverse. Any of them may have a displacement parallel to the strike of the fault, or perpendicular to it, or oblique to it.

The direction of displacement, whether parallel, perpendicular, or oblique to the strike of the fault, is a further means of classifying faults according to their geometric relations. Thus:

- (1) A fault on which one wall has slipped past the other in a direction parallel to, or nearly parallel to, the strike of the fault is a *strike-slip fault*.
- (2) A fault on which one wall has slipped past the other down the dip of the fault, or has been pushed past the other up the dip of the fault, is a *dip-slip fault*.
- (3) A fault on which the walls are displaced in a direction oblique to the strike of the fault is an *oblique-slip fault*.

The dip-slip type is the oldest type of fault recognized and is the one most commonly described. The effect of a dip-slip is

however, very often simulated by slips in other directions, and the tendency to assign all faults to this type is frequently misleading.

The movement on an oblique-slip fault is in a direction which makes an acute angle with the strike of the fault. The effect may actually be, or may appear to be, that of a normal fault or of a reverse fault.

It is important to avoid the confusion which may arise between the terms oblique fault and oblique-slip fault, recalling that an oblique fault is one whose strike forms an acute angle with the *strike of the strata*, whereas an oblique-slip fault is one whose displacement is at an acute angle with the *strike of the fault*. An oblique fault may be a strike-slip, dip-slip, or oblique-slip fault and an oblique-slip fault may be a strike fault, a dip fault, or an oblique fault. We have two kinds of classes. The first depends upon the relation of the strike of the fault to the strike of the strata, the second upon the direction of movement on the fault plane. The former is determined when we observe the strikes of the fault and strata, whereas the latter can be fixed only by ascertaining the true direction of the slip or push.

Strike faults which trend with the general structure of a region are called *longitudinal faults*, whereas dip faults which cross the general structure are called *transverse faults*. These terms find their application in descriptions of large areas and great structures.

Nomenclature of Faults.—Faults and fault displacements have many names, and unfortunately the names are used in various senses by different groups of technical men. There are the miners and the mining engineers, whose terms are few and comprehensive; fault, slip, throw, and heave are employed to designate a variety of structures or displacements and consequently have no exact meanings. There are geologists in general, who follow the usage of textbooks, which are many of them not up with current discussion. And there are specialists in fault structures, who have developed a modern, technical use of terms that has the advantage of being exact, but is understood by but few. The writer who would not be misunderstood must, therefore, take pains to make his meaning obvious.

Very early in mining it became necessary to distinguish the

amount of vertical displacement occasioned by a fault from the horizontal displacement. Consider a right angle triangle and let the hypotenuse represent a fault plane along which horizontal strata have been displaced. Let the triangle stand with one side horizontal, the other vertical. Then, if the length of the hypotenuse represents the *slip* on the fault plane, the horizontal side will be the horizontal component of that displacement, called the *heave* of the fault, whereas the vertical side will be the vertical component of the displacement, called the *throw* of the fault.

Throw and heave thus correspond respectively to the vertical and horizontal sides of a right angle triangle, of which the dip-slip is the hypotenuse. These three simple terms suffice in general to describe the dimensions of a fault. The slip (first published in 1913 with this meaning) is the displacement on the fault plane, which geologists too often erroneously call the throw. It indicates the real magnitude of the movement, whether it is given in feet, thousands of feet, or miles. The ratio of the throw to the heave indicates the attitude of the fault plane, since when the throw is twice or more than twice the heave we have a decidedly high-angle fault (dip, 27 degrees or less), whereas if the throw is only half the heave or less we have a distinctly low-angle fault or thrust (dip, 27 degree or less).

Exact statements, however, require that the position of the vertical plane formed by these three hypothetical lines should be defined with reference to the strike of the fault, and to avoid inconveniences of statement and interpretation the rule is laid down that *throw and heave shall be taken in a plane at right angles to the strike of the fault*.

The corresponding slip will also lie in this plane, the plane of the dip of the fault, and to distinguish it from slips in directions oblique to the vertical or even horizontal, it is called the *dip-slip*.

Throw, heave, and dip-slip are the elements of a fault in the dip-plane only, and they are, therefore, adequate to describe the movement only in case the displacement has been directly up or down the dip-plane. If there has also been horizontal movement, a fourth element is required to represent the horizontal component of the true displacement. This element, when measured horizontally in the fault plane, corresponds in direction with the strike of the fault and is therefore called the *strike-slip*.

To illustrate: the earthquake on the San Andreas fault in

1906 occasioned a vertical displacement of about one foot and a horizontal displacement of 20 feet. The hade of the fault is nearly vertical. Stated in fault terms this would read: The throw was about one foot and nearly the same as the dip-slip. The heave was very small. The principal movement was in the direction of the strike-slip and amounted to as much as 20 feet.

It is a common practice of geologists to draw sections at right

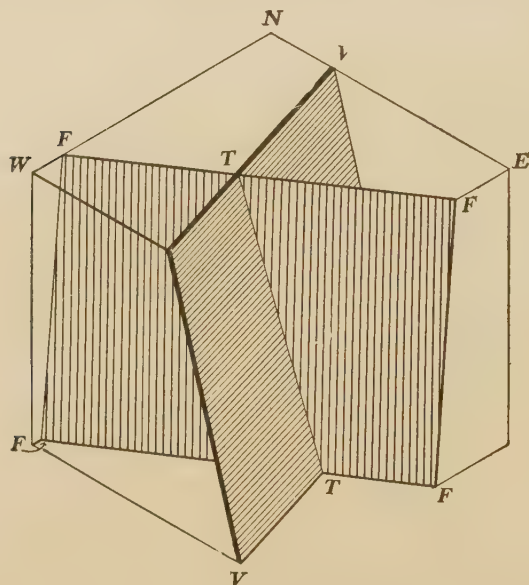


FIG. 68a.—View of the intersection of two planes without displacement, as seen in isometric perspective.

FF a plane.

VV a plane.

TT trace of *FF* with *VV*.

WNE corners of the isometric cube. The front of the cube is removed.

angles to the strike of strata and without reference to the strike of any faults which may traverse them. The strike of the strata and that of the faults often differ, and the dimensions of the throw, heave, and dip-slip of the faults differ correspondingly in a section at right angles to the strata from those which they would have in a section at right angles to the strike of the fault. Therefore, when it is desirable to draw sections in any other position than

normal to the strike of the fault, the dimensions obtained for the elements of the fault should be stated as the apparent throw, heave, and dip-slip, to distinguish them from the true values of those components of the movement.

In general geologic studies, in which we deal with large masses of strata, whose visible section is restricted to surface outcrops, all the rest being either eroded or buried, it is rarely possible to measure the displacements of faulted mountain blocks with

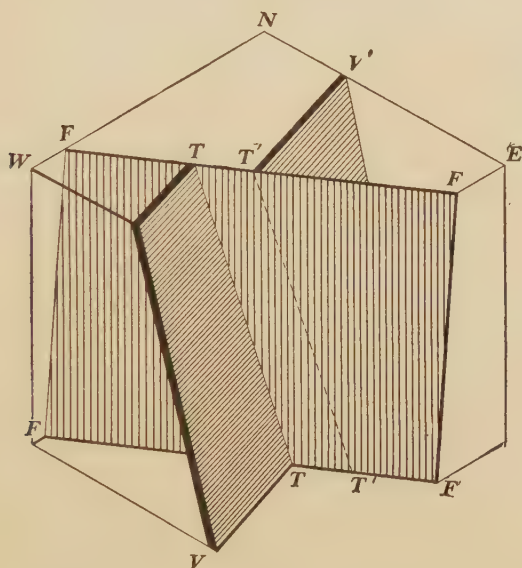


FIG. 68b.—View of the intersection of two planes with displacement, as seen in isometric perspective.

FF fault plane.

TV and *T'V'* segments of the plane *VV'*, which has been displaced.

TT and *T'T'* traces of the fault plane *FF* with the segments of the faulted plane.

WNE corners of the isometric cube, the front of which is removed.

accuracy, and mathematical niceties of definition are too often overlooked. Geology suffers accordingly, for loose language is the expression of loose thinking and leaves the reader in doubt as to the value of the observations which it records.

In mining, on the contrary, precise surveys above and below ground govern all well-conducted operations and precision in

observation demands exactness in statement. The proper use of fault terms should, therefore, be the rule. It is not, however, partly because language is often used carelessly, partly because



FIG. 69.—Illustration of faulting in the Aspen district, Colorado. Geologic map of Tourtelotte Park. (After Spurr. U. S. Geol. Surv., *Monograph XXXI*, Scale: 1 inch = 3,000 feet.)

the development of the terminology of faulting is comparatively recent and has not yet become widely known. The exact definition and precise usage of the terms employed in describing faults

is, none the less, imperative in the interest of the proper understanding of fault mechanics.

Spurr¹ first called attention to the fact that displacements accompanying faulting might take place in any direction. He wrote:

In this movement one part of the fractured rock mass may move upon the other in any direction—up, down, sidewise, or obliquely—according to the conditions, which are different in each instance.

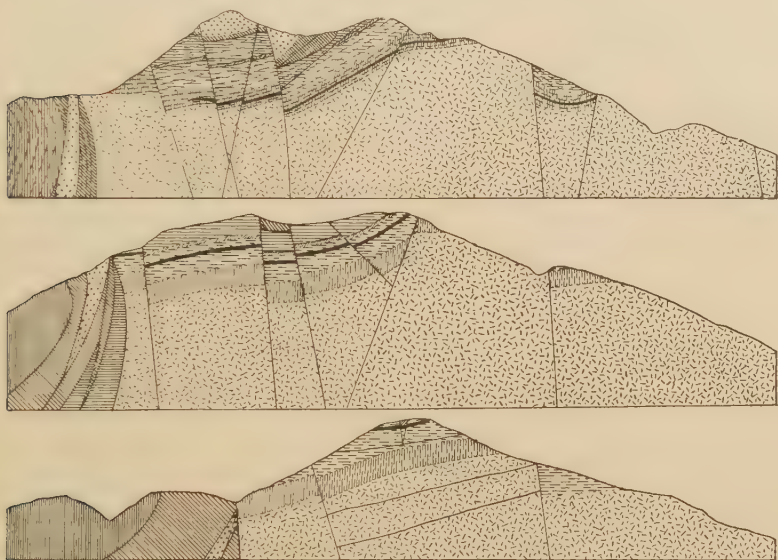


FIG. 70.—Illustrations of faulting in the Aspen district, Colorado. Sections of Tourtelotte Park, looking north. (After Spurr. Scale: 1 inch = 3000 feet.)

He recognized that oblique movements require more precise terms to define their components than those which had sufficed under the assumption of direct up and down movements, and he proposed a set of six names to designate different parts of a fault movement, namely:

For general outline work, where accurate data are not obtainable, the terms *throw* and *vertical separation*, referring to the measurements of a fault at its intersection with a vertical plane, and the term *heave* or *offset*,

¹ SPURR, J. E., *Geology of the Aspen Mining District, Col.* U. S. Geol. Surv., *Monograph XXXI*, Appendix, pp. 253 to 256, 1898.

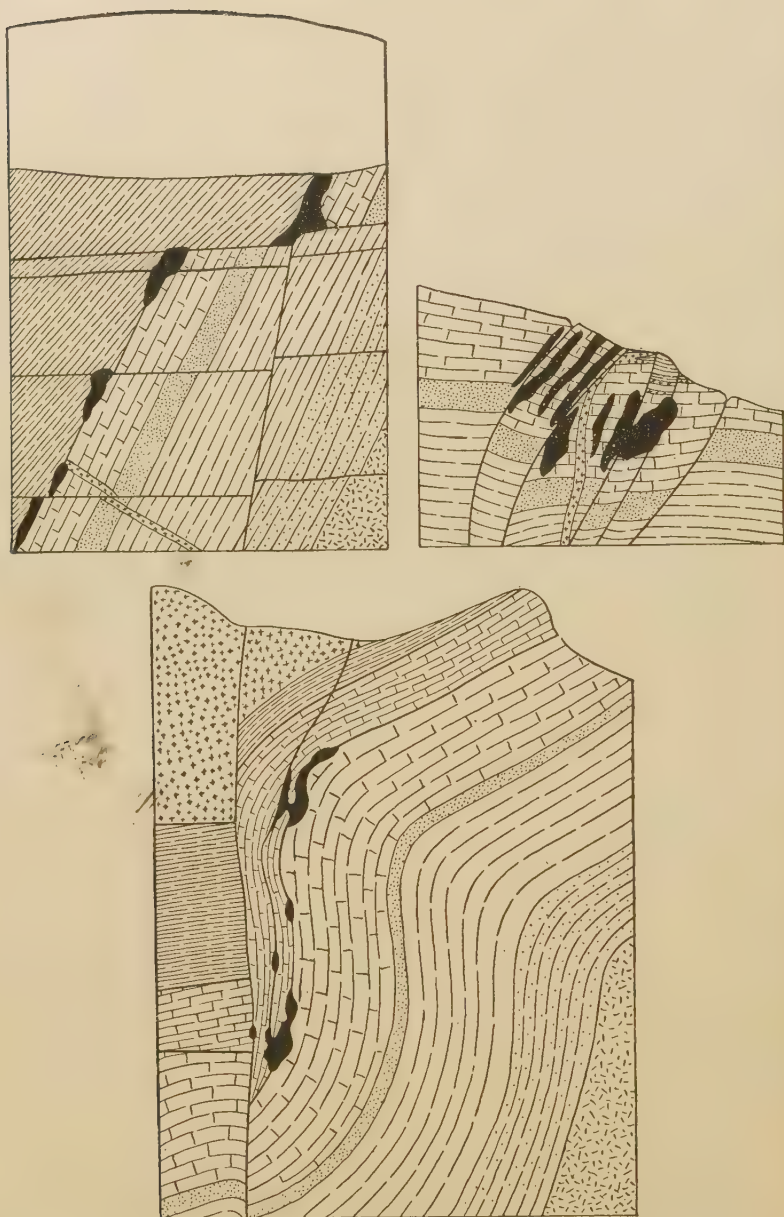


FIG. 71.—Sections from the Aspen district, Colorado, illustrating the deposition of ore bodies (black) in relation to faults.

indicating the measurement of a fault at its intersection with a horizontal plane, are adopted. . . . Where more complete data are obtainable, the terms *total displacement*, *lateral separation*, and *perpendicular separation* are adopted.

Spurr's proposed terms did not come into general use, largely because very few writers discussed faults with sufficient exactness to employ precise names for the details of movements and also because his terms did not agree in meaning with previous usage, especially the two old terms, throw and heave. Their meaning is given in relation to that of other systems on page 112.

Ransome¹ pointed out that:

The terms normal and reverse as commonly applied to faults have very little real significance. They express merely a location of the faulted beds, dikes, or other structures to the plane of the fault. They do not, unless we make unwarranted assumptions, indicate the kind or direction of movement or whether tension or compression was the dominant stress at the time of dislocation.

The stress of Ransome's paper is upon the occurrence of horizontal movements on fault planes and he rightly emphasizes the fact that such movements are far too common to be overlooked, as had been done by even the best writers. The gist of his argument is expressed in the excellent diagrams taken from his paper, Fig. 48, *a*, *b*, *c*, and *d*.

Tolman² in 1911 proposed a very elaborate and logical system of fault nomenclature, developed as a result of his experience with fault problems in mining practice and in teaching. He groups the possible measurements under the names of "displacements, throws, heaves, and separations," and distinguishes under each name five different measurements, which bear certain definite relations to the fault plane, to vertical and horizontal planes, and to the plane of the faulted vein or stratum. His terms are defined in the following paragraphs, along with those proposed by the committee appointed by the Geological Society of America.

Following a discussion of fault movements, which was pub-

¹ RANSOME, F. L., *The Directions of Movement and the Nomenclature of Faults*, *Econ. Geol.*, vol. 1, pp. 777 to 787, 1906.

² TOLMAN, C. F., Jr., *How Should Faults Be Named and Classified?* *Econ. Geol.*, vol. II, pp. 506-511, 1907.

lished in *Economic Geology*,¹ the Geological Society of America named a committee to draw up and propose a nomenclature of faults, which submitted its final report at the meeting of December, 1912.² The conclusions of this committee, whose work extended over three years and comprised the consideration of all published material pertaining to the subject, as well as correspondence with a wide circle of geologists, are worthy of being followed, as representing the nearest approach to an agreement in discussions involving technical precision in descriptions of the complex movements of faulting. The terminology recommended by the committee is accordingly given precedence in the following statement of the modern terminology of fault displacements.

It is assumed that the reader is familiar with the methods of projection used in the simpler problems of descriptive geometry. It is only by their use that we can represent the position of any line in space. They enable us to present it in its true dimension, or according to some scale that we can determine, in a plane which we assume to suit our convenience. They thus make it possible for us to see and to measure the lines that represent movements of masses in the earth, which are actually buried beyond observation or which have been eroded. Any builder uses these methods when he draws the plan or elevation of a house on a sheet of paper. He assumes that the paper is parallel to the floor or to the wall of the building and he projects the lines representing the length, width, or height upon the paper according to the scale which he has adopted. We use similar projections in the study of earth structures, including faults.

The thing which we measure in faults is the displacement of one mountain mass with reference to another with which it was formerly connected; or the distance by which one part of a dissevered stratum or vein is separated from the other part; or the exact length of a line which we draw to connect a known point on one side of the fault with the point which was in contact with the first before the displacement occurred.

There are five planes on any one of which the components of displacement may be measured. They are:

¹ *Econ. Geol.*, vol. 2, pp. 58, 182, 295, 433, 506, 585, 601, 803; 1907.

² REID, H. F., DAVIS, W. M., LAWSON, A. C. and RANSOME, F. L., Report of the Committee on the Nomenclature of Faults, *Bull. Geol. Soc. Am.*, vol. 24, pp. 163-186, 1913.

- (1) The fault plane itself.
- (2) The dip plane of the fault.
- (3) The dip plane of the strata or of the vein.
- (4) The plane perpendicular to the trace of the fault with the strata or vein.
- (5) The horizontal plane.

According to the beautifully systematic nomenclature proposed by Tolman, all measurements made in the fault plane should be called *displacements*, all those in the dip-plane of the fault should be *throws*, all those in the plane perpendicular to the trace should be *separations*, and all in the horizontal plane should be *heaves*.

The committee of the Geological Society of America endeavored to assemble a group of terms which would "make no changes in words which have a recognized meaning" and would "follow the best usage where a word is used in different senses." The result is therefore necessarily unsystematic. According to the conclusions of the committee certain terms have the following applications:

Displacement is a general term by which to designate the relative movement of the two sides of a fault, measured in any direction.

Slip designates any measurement in the fault plane. The slip in a specific direction may be distinguished by an appropriate adjective and we thus get *dip-slip*, denoting the slip in the direction of the dip of the fault, and *strike-slip*, referring to the component of the displacement parallel to the strike.

Shift is introduced to describe the displacement of masses on either side of a complicated fault zone. Its use implies that the shifting of the masses has been occasioned by movements on two or more related faults, distributed in a zone of greater or less width. The terms *dip-shift* and *strike-shift* designate the components of movement in the direction of the resultant dip or strike respectively. Shifts are measured parallel to the zone of faulting, to its dip or strike, etc., the general position of the zone taking the place of the attitude of the fault surface of a clean-cut fault.

Separation is proposed as a word of rather general significance, to be applied to measurements between the two surfaces of the faulted bed or vein, taken in any direction. Thus, in mining, a

tunnel, driven through a fault from the vein on one side to the same vein on the other and measured from footwall to footwall or from hanging to hanging, would give the horizontal separation in that particular direction. A shaft, similarly located and measured, would represent the vertical separation.

Throw is restricted by the committee to the vertical distance between the two ends or edges of a faulted bed or vein, taken in a plane at right angles to the strike of the fault.

Heave is similarly restricted to the horizontal distance between the two ends or edges of a faulted bed or vein, taken in a plane at right angles to the strike.

The preceding definition of throw and heave is made more exact by the insertion of the requirement that the elements shall be measured between the edges of the severed stratum or vein. Any other vertical or horizontal measurement is excluded. Thus, if we have a dip-fault which crosses an inclined stratum whose traces with the fault plane are shown in Fig. 72 as *ac* and *bd*, the throw is *bk* and not *cf*, while the heave is *ak* and not *ae*.

Geologists wishing to designate the horizontal distance between the two occurrences of a displaced stratum, or mining engineers describing the driving of a tunnel from one segment of a vein through a fault to the other part, may refer to *ae* as the heave of the fault; but that is not according to the definition. The line *ae*, if measured in a plane at right angles to the strike of the fault, represents the *horizontal separation*, according to the committee; or, if it is measured in the plane at right angles to the strike of the strata, it is the *offset* or *normal horizontal separation*.

It has been stated that the dimensions of faults may be measured in any one of five planes, enumerated on page 107. Of the five there are two which are employed either by one or the other of two groups of students, but usually not by both. The dip-plane of the strata is a plane of projection preferred by geologists, but less used by miners; and the plane perpendicular to the trace of the fault with the vein is a reference plane used only by a few mining engineers. In Tolman's ¹ classification the former was not

¹ TOLMAN, C. F., Jr., How Should Faults Be Named and Classified? *Econ. Geol.*, vol. II, pp. 506-511, 1907.

considered, whereas in that of the committee the latter was not recognized.

The details of the authoritative nomenclature of faults as formulated by the committee of the Geological Society of America¹ are given in the accompanying diagrams and the appended descriptions. Tolman's names are also stated. For the arguments which governed the committee, the original paper should be consulted.

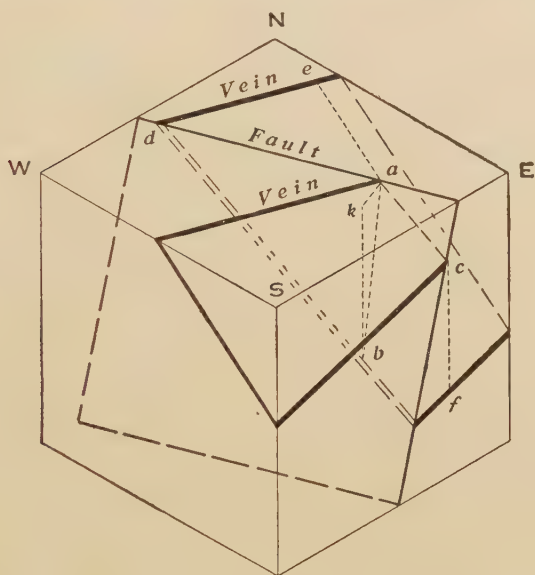


FIG. 72.—View of a dip-fault.

ac and *db*. Trace of faulted vein on fault.

bk. Throw.

ak. Heave.

In order that they may have definite meanings the names of fault measurements are referred to certain lines and directions and are taken in certain planes, all of which are shown in Fig. 73, which represents a fault plane, a fault, the faulted vein, and three other planes.

The fault plane is *FFFF*. The faulted vein is *VVTT* in

¹ REID, H. F. and others. Report of the Committee on the Nomenclature of Faults; *Bull. G. S. A.*, vol. 24; pp. 163-186, 1913.

front of the fault plane and $V'T'T'V$ behind it. The traces of the vein with the fault plane are TT and $T'T'$, and we may see that TT appears to have slipped down from its former position in contact with $T'T'$. Thus the fault has the appearance of a normal displacement, but it may be noted that the same effect would be produced by a horizontal shift of the front block from the right, where TT might have been in contact with $T'T'$, toward the left to its present position. The character of the fault is, therefore, indeterminate.

Three planes, $Df-Df$, $Dv-Dv$, and $Pt-Pt$, are shown cutting across the fault plane and the faulted vein. An infinite number of planes might be laid across the system, but these three are selected because each one has a definite mathematical relation to either the fault plane or the vein or the trace of the vein with the fault plane.

$Df-Df$ is a vertical plane which makes a right angle with the strike of the fault. The trace, FF , which the fault plane makes with the horizontal upper surface of the cube, is the strike of the fault, and the angle which it makes with $Df-Df$ is 90 degrees. $Df-Df$ is the dip plane of the fault.

$Dv-Dv$ is a vertical plane which makes a right angle with the strike of the vein. The trace, VV , which the vein makes with the horizontal upper surface of the cube, is the strike of the vein, and the angle which it makes with $Dv-Dv$ is 90 degrees. $Dv-Dv$ is the dip plane of the vein.

$Pt-Pt$ is a plane which is laid perpendicular to the trace, TT , of the vein with the fault plane. It is therefore inclined to the horizon in all cases except when TT is horizontal. $Pt-Pt$ is perpendicular to both the fault plane and the vein, the angles made by its traces with the fault plane and the vein being right angles. $Pt-Pt$ does not, however, cut the strike of either the fault or the vein at 90 degrees.

Measurements of the displacement of a fault may be made in any plane whatever, chosen for convenience in a particular case; but for general discussion the useful planes are limited to five in number. They are: (1) the fault plane, itself, $FFFF$ in Fig. 73; (2) the dip plane of the fault, $Df-Df$; (3) the dip plane of the vein, $Dv-Dv$; (4) the plane perpendicular to the trace of the vein with the fault plane, $Pt-Pt$; and (5) the horizontal plane, $NESW$.

In order to present clearly the accepted measurements in each of these planes, isometric views of a fault similar to that shown in Fig. 73, have been prepared to present each of the planes to the eye separately and in the foreground. The cube has been turned about and the front of it omitted where necessary to dis-

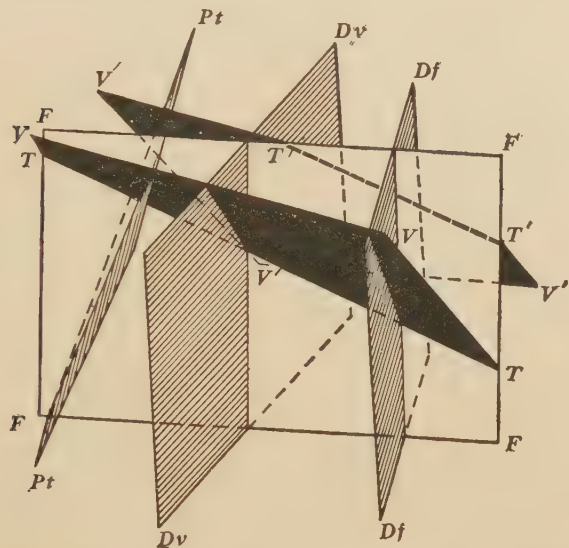


FIG. 73.—Diagram of the planes in which systematic measurements of displacements are made in studying faults.

Isometric projection of an oblique, normal fault. *FFFF* is the fault plane. *VVT* and *V'T'V'* are the separated parts of the vein. *TT* and *T'T'* are the traces of the fault plane with the vein.

Three planes are shown cutting across the faulted vein and fault plane. They are *DfDf*, which is laid at right angles to the strike of the fault and is the dip plane of the fault; *DvDv*, which is laid at right angles to the strike of the vein and is the dip plane of the vein; and *PtPt*, which is laid at right angles to the trace of the fault with the vein.

These three planes, together with the fault plane and a horizontal plane, are those in which the displacements of faults are measured, as is explained in the figures that follow.

tinctness of the important features. The orientation of the cube can be seen by reference to the letters *NESW*, which stand for the points of the compass and hold a fixed relation to the assumed fault.

Figure 74 represents an apparently normal, oblique fault, which has displaced a vein by the amount indicated by the distance between TT and $T'T'$, the two traces of the vein with the fault plane. It is assumed that a point V' is represented after faulting at V'' and under that assumption the fault is normal. The line $V'V''$ is in the fault plane and is inclined to the vertical. As assumed it does not lie in the dip plane of the fault. $V'a$, $V''a$, $V'b$, and $V''b$ are lines drawn in the fault plane. They thus lie in one and the same plane with $V'V''$ and they form with that line two right angle triangles.

$V'a$ is in a vertical plane and is the trace of that plane with the fault plane. It corresponds with the dip of the fault. $V''a$ is in a horizontal plane and is the trace of that plane with the fault plane. It corresponds with the strike of the fault. $V'b$ is part of the trace of the vein with the fault plane. And $V''b$ is the trace of the fault plane with a plane which makes a right angle with the trace of the vein and the fault.

Slip is the term adopted by the G.S.A. committee to designate any component of displacement, measured in the fault plane. Slip may be measured in any direction in that plane, but the components described above are those usually required to analyze a fault movement and they are given special names. $V'V''$ is the net or total slip. $V'a$ is the dip-slip. $V''a$ is the strike-slip. $V'b$ is the trace-slip. And $V''b$ is the perpendicular slip.

The term slip in the sense of a function of displacement measured in the fault plane is excellently selected, and the qualifying terms, net, dip, strike, trace and perpendicular connote definite relations, so that they are easily understood. They should be generally adopted and used.

Spurr had previously suggested the use of "throw" for $V'a$ and "lateral separation" for $V''b$. Tolman employed "displacement" in the specific sense in which the Committee uses "slip" and, recognizing the five special measurements, called them "total, normal, horizontal, parallel, and perpendicular displacements." Thus in his terminology "normal" corresponds to "dip," *i.e.*, measured in a vertical plane; "horizontal" to "strike"; and "parallel" to "trace" of the Committee's terminology.

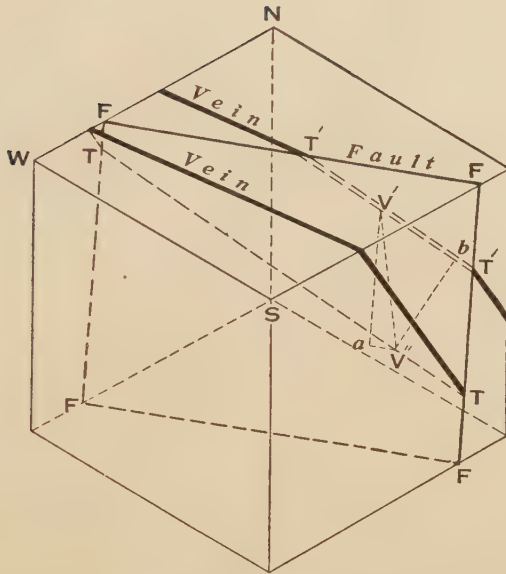


FIG. 74.—View of a normal, oblique fault, looking at the fault plane, *FFFF*.

Displacements.—The displacements of the vein are here shown projected on the fault plane itself. They are variously designated by different authorities as follows:

G. S. A. Committee	Tolman
$V'V''$	Slip or net slip.....
$V'a$	Dip-slip.....
$V''a$	Strike-slip.....
$V'b$	Trace-slip.....
$V''b$	Perpendicular slip.....
	Total displacement
	Normal displacement
	Horizontal displacement
	Parallel displacement
	Perpendicular displacement

NOTE.—The term *slip*, which is in common use among miners in referring to any break in the rocks, is given a special meaning by the Committee of the Geological Society, it being used by them to designate movements measured on the fault plane, with the qualifying prefixes given above to distinguish movements, as shown in the figure. Tolman proposed the use of *displacement* for the same measurements and applied the distinguishing adjectives which he uses throughout his logical system of fault nomenclature. In this work we follow the Committee in using *displacement* in the most general sense and employing *slip* for the measurements in the fault plane.

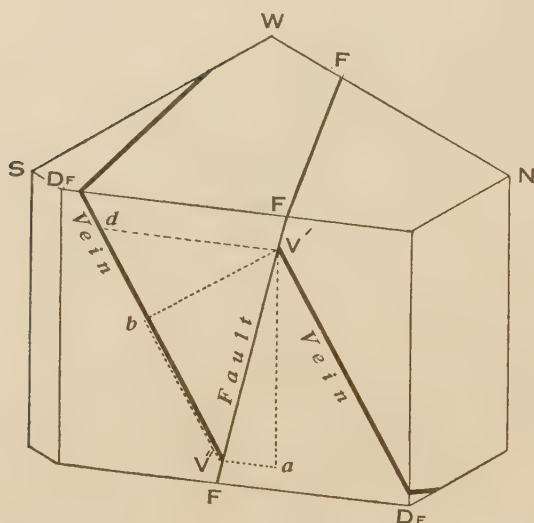


FIG. 75.—View of a normal oblique fault, similar to that shown in Fig. 70, but viewed looking at the dip plane of the fault, that is, at right angles to the view.

Displacements.—Those displacements measured in the dip plane of the fault are variously designated as follows (see Figs. 74 and 76).

	G. S. A. Committee	Tolman
$V'V''$	Slip for a dip-slip fault, or apparent slip for an oblique-slip fault...	Total throw
$V'a$	Throw.....	Normal throw
$V''a$	Heave.....	Horizontal throw
$V'b$	Apparent stratigraphic separation...	Perpendicular throw
$V''b$	No name.....	Parallel throw
$V'd$	Apparent offset.....	No name

NOTE.—All the above measurements are made in the dip plane of the fault. It will be noted that in this plane lie the throw and heave, as defined by the G. S. A. Committee, whereas the other measurements are qualified as having only the apparent, not the true dimensions. This qualification arises from the fact that the movement on the fault plane may have been in any direction, not necessarily in the direction of the dip-slip.

Tolman adopts the term *throw* for all measurements in the dip plane of the fault and applies the systematic terms that describe the several measurements under his nomenclature.

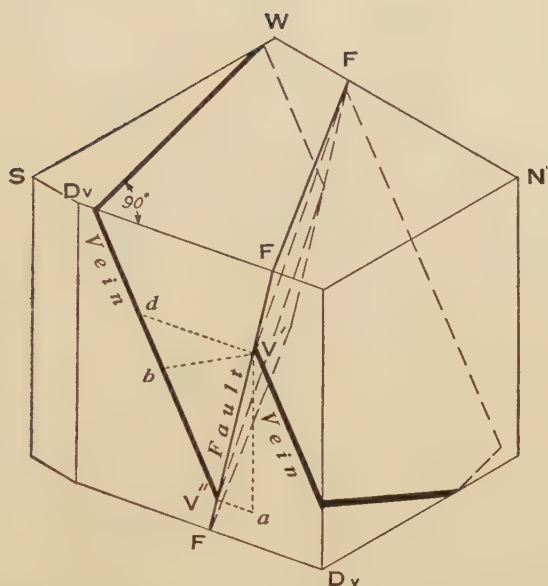


FIG. 76.—View of an oblique fault, similar to that shown in Fig. 74, but viewed looking at the dip plane, D_v , of the vein.

Displacements.—Displacements measured in the dip plane of the vein are designated as follows by the G. S. A. Committee. Tolman gave no names to measurements in this plane.

	G. S. A. Committee
$V'V''$	Apparent slip
$V'a$	Apparent throw
$V''a$	Apparent heave
$V'b$	Stratigraphic separation
$V''b$	No name

NOTE.—All the possible measurements in this plane, with the exception of the stratigraphic separation, are apparent rather than true measurements of the actual displacements in a given direction, unless the movement on the fault has been parallel to the dip of the vein or strata. This condition would rarely be met with in the case of faulted veins, but may occur where faulting has been directed by the bedding planes of strata. The stratigraphic separation is an important measurement in general geologic work, but is usually of less consequence in mining.

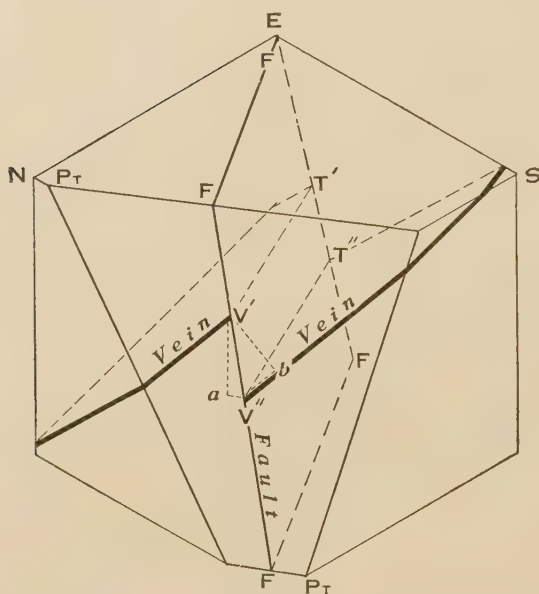


FIG. 77.—View of an oblique fault similar to that shown in Fig. 73, but viewed looking at a plane laid perpendicular to the trace of the vein with the fault plane, *i.e.*, P_t in Fig. 73.

Displacements.—Measurements in the plane perpendicular to the trace of the vein and the fault plane are practically confined to mining practice and were not considered by the G. S. A. Committee. Tolman has named them as follows:

	Tolman
$V'V''$	Total separation
$V'a$	Normal separation
$V''a$	Horizontal separation
$V'b$	Perpendicular separation
$V''b$	Parallel separation

NOTE.—The important measurement in this plane is $V'V''$, the total separation, for it is the shortest distance between the two traces of the vein with the fault plane. Among the other measurements the perpendicular separation is the shortest distance between the two parts of the vein and is the same as the stratigraphic separation as defined by the G. S. A. Committee. (Fig. 76.)

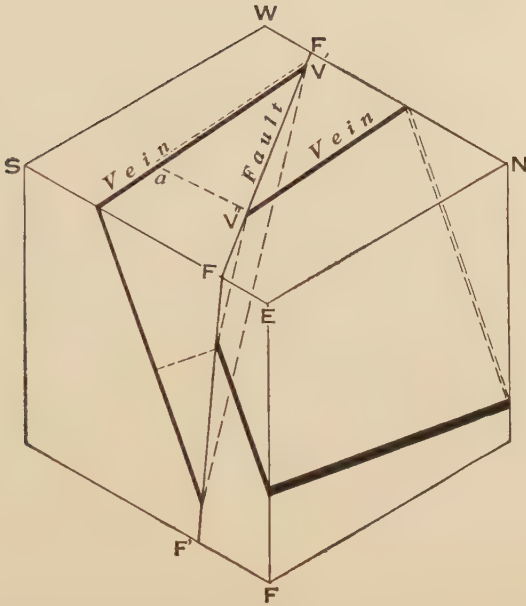


FIG. 78.—Fault Measurements in a Horizontal Plane.

G. S. A. Committee

Tolman

$V'V''$	Strike slip.....	Total heave
$V''a$	Offset ("Heave," Geikie)...	Perpendicular heave
$V'a$	Overlap*	Parallel heave.

* Called "Gap" in case there is a space between V' and V'' in which the vein is missing.

CHAPTER VI

CLEAVAGE

Definitions.—To split or to cleave are English synonyms with a slight difference of meaning which leads us to say that a rock cleaves rather than that it splits. The word *cleave* carries the idea of parting along a flat, smooth surface, the characteristic parting of rocks. Split admits of the same interpretation, but is not so definitely limited to a plane parting. Hence we speak of rocks cleaving rather than splitting and use the noun *cleavage* rather than split.

Cleavage in rocks has been studied by many eminent investigators, beginning with Sedgwick in 1829, but it was not until Van Hise and Leith carried out their exhaustive studies that the complexities of the phenomena were unraveled. Van Hise published his results in several papers¹ and was followed by Leith² after ten years more of thorough investigation.

These researches may be regarded as having established beyond question the conditions that determine rock cleavage.

Van Hise states them as follows:³

Rock cleavage is due to the arrangement of the mineral particles with their longer diameters or readiest cleavage, or both, in a common direction, and this arrangement is caused: first and most important, by parallel development of new minerals; second, by the flattening and parallel rotation of old and new mineral particles; and third and of least importance,

¹ VAN HISE, C. R., Principles of North American Pre-Cambrian Geology, U. S. Geol. Surv., *Sixteenth Annual Rept.*, pt. 1, pp. 633-668, 1896. Deformation of Rocks, pt. 3, Cleavage and Fissility, *Jour. Geol.*, vol. 4, pp. 449-483, 1896. Metamorphism of Rocks and Rock Flowage, *Bull. G. S. A.*, vol. 9, pp. 269-328, 1898. A Treatise on Metamorphism, U. S. Geol. Surv., *Mon.*, vol. 47, pp. 748-763, 1904.

² LEITH, C. K., Rock Cleavage, U. S. Geol. Surv., *Bull.* 239, 1905.

³ VAN HISE, C. R., Principles of North American Pre-Cambrian Geology, U. S. Geol. Surv., *Sixteenth Annual Rept.*, p. 635, 1896.

by the rotation into approximately parallel positions of random original particles.

The validity of this statement was confirmed by Leith,¹ who amplified the explanation of the conditions governing cleavage as follows:

In the rocks with secondary flow cleavage examined during this investigation, which are believed to be fairly representative of such rocks in general, a plane, or surface of cleavage has been observed to be uniformly parallel to the greatest and mean, or greatest and least dimensions, or both, or even to the greatest alone, of the parallel constituent mineral particles. This has been observed macroscopically in thousands of specimens, and microscopically in several hundred prepared slides. Not only has a cleavage been observed to coincide with the longer diameters of the parallel particles, but it has been apparent that the excellence of such cleavage is proportional to the degree of the arrangement and to the inequality of the dimensions of the particles. In addition to this essential condition of parallel arrangement, another condition, dependent on the first, has been observed to be of great importance—the parallel arrangement of mineral cleavages. This has usually aided the dimensional arrangement, but has rarely tended to cause a cleavage in a plane different from that caused by the dimensional arrangement of the mineral constituents.

It is apparent that certain minerals, possessing the quality of breaking or crystallizing in flat or elongate forms, will more perfectly produce cleavage than others whose habit of form is rounded. It is also true that minerals tend to develop in harmony with their dynamic environment. Therefore, if it were possible for either one of several minerals to develop at a given point and the pressures at that point favored the growth of flat or elongate minerals, they would be the ones that would form and they would give rise to cleavage. Rock cleavage is thus related to a few minerals, which Leith enumerates as the constituents of the bulk of cleavable rocks. He says:

The micas, including muscovite and biotite, chlorite, hornblende, quartz, and feldspar, are in greatest abundance, making up, perhaps nine tenths of them. Other minerals, characteristic though less abundant, are calcite, tremolite, actinolite, garnet, tourmaline, staurolite, chloritoid, sillimanite, etc.

¹ *Op. cit.*, p. 49.

The dynamic conditions under which these minerals might develop in such a way as to produce a cleavable rock have been the subject of much discussion. Van Hise and Leith made a fundamental contribution to the knowledge of the phenomena by demonstrating that there are several kinds of rock cleavage and that they differ in the conditions of their origin. They classified rock cleavage accordingly, and Leith¹ finally threw the classification into the following form:

CLASSIFICATION OF CLEAVAGE

(According to Van Hise and Leith)

Rock-cleavage. (Cleavable rock.)	{	<i>Original cleavage.</i> (Protoclase or original-cleavage rock.)	
		Bedding.	
		Flow structure in lavas.	
		Parallel structure in certain gneisses.	
		Pegmatitic structure.	
		Parallel structure due to the arrangement of feldspars in certain gabbros, etc.	
		{	<i>Flow cleavage.</i> Including in whole or in part:
			"Ultimate cleavage" of Sorby,
			"Cleavage" of most writers, "Slaty cleavage," "Cleavage proper," etc.
			Schistosity. (Schists.)
			Slatiness. (Slates.)
			Parallel structure in certain gneisses.
			(Comes partly under schistosity.)
		<i>Secondary cleavage.</i> (Metaclase or secondary cleavage rock.)	
		{	<i>Fracture cleavage.</i> Including in whole or in part:
			Close joints cleavage.
			False cleavage.
			Strain slip cleavage.
			Ausweichungs cleavage.
			Fissility in part. (The term is retained for closely spaced, parallel partings.)
			Rift.

The preceding classification of cleavage is the result of a very comprehensive study, extended over twenty years and intensified by controversy. It comprises, therefore, all possible structures

¹ *Op. cit.*, p. 12.

to which the term cleavage can be applied and more than are usually included under that term. Thus, bedding and flow structure in lavas are not called cleavage, although the rocks possessing these structures have a capacity to part along parallel surfaces. Certain gneisses, on the other hand, exhibit an original arrangement of minerals in parallelism which results in original cleavage. They and similar originally cleavable, crystalline rocks may properly be called *protoclase*.

In general, the term cleavage covers only the secondary structures, those which are a result of recrystallization or of shearing of the rock subsequent to its original consolidation. Such rocks fall into the class of the *metaclases*.

Attention may well be concentrated on the distinction between fracture cleavage and flow cleavage, which is stated by Leith as follows:

Fracture cleavage is conditioned by the existence of incipient, cemented, or welded parallel fractures, and is independent of a parallel arrangement of the mineral constituents. *Flow cleavage* is conditioned solely by a parallel arrangement of the mineral constituents.

The importance of this distinction lies in the relation which the direction of the cleavage bears to the major force affecting the rock mass at the time of the development of the structure, whichever it may be. For the complete discussion reference should be made to Leith's presentation. It had been held by some that all cleavage developed in a direction at right angles to the major pressure, whereas it was maintained by others that all cleavage grew in a plane inclined to that pressure. According to the former, the direction of cleavage represented the normal plane, whereas according to the latter it represented a shearing plane.

Van Hise demonstrated that there is a cleavage developed in the normal plane, which he called "flow cleavage," and that there is a different kind of cleavage that develops in the shearing planes, to which he and Leith finally gave the name "fracture cleavage." The recognition of the two great classes, characterized by distinct features and bearing different relations to the direction of the major pressure at the time of their growth, was a definite advance.

Subsequent studies have, nevertheless, led Leith to recognize that the distinction between cleavage developed at right angles to the major pressure and that developed parallel to shearing

planes inclined to the major stress cannot be established in many cases. He expressed this view as follows:¹

The interpretation of rock cleavage or schistosity, a common though not the only evidence of rock flowage, affords an especially good illustration of the danger of using narrow assumptions as to its relations to causal stresses. Cleavage is a capacity to part along parallel surfaces determined by the parallel dimensional arrangement of mineral particles. There is abundant proof that the schistose rock has been elongated parallel to the cleavage surface, and cleavage thus becomes evidence of elongation. It does not follow, however, that the stress producing elongation was applied normal to it.

The further discussion of the mechanical conditions of rock shear is deferred to another chapter (page 166). We here take up its relations to other structures, such as stratification and folding.

Secondary cleavage is independent of bedding. Already in 1835 Sedgwick² stated this fact from his observations in the mountains of north Wales. He wrote:

The whole system of slates and tabular porphyries has been thrown into a number of great undulations, producing through the chain a series of longitudinal anticlinal and synclinal lines. Parallel lines of cleavage not merely affect given beds, but sometimes run, without deviation, even through coarse mechanical subordinate strata, affecting whole ranges of mountains and preserving their parallelism in spite of undulations and anticlinal lines.

Sedgwick's observation has been confirmed by many observers. Regional cleavage or schistosity maintains its course independently of the strike of the stratification in folded strata. Heim³ formulated a law of parallelism between the strike of strata and that of cleavage, but it is to be noted that the folds of the Alps which he studied were so closely compressed that the strikes of the strata are parallel to the axes of the anticlines and synclines. Now cleavage does run parallel to the axes of the folds, as he also observed, and therefore parallel to the strike of the bedding where compression has been excessive, but, remaining parallel to the axes, it cuts across the strata where they strike at an angle to the axes, as they do in open pitching folds.

¹ LEITH, C. K., The Structural Failure of the Lithosphere. *Science*, vol. LIII, p. 198, 1921.

² SEDGWICK, ADAM, Remarks on the Structure of Large Mineral Masses, etc., *Trans. Geol. Soc., London*, second ser., vol. 3, pt. 1, pp. 461-468, 1835.

³ HEIM, ALBRECHT, "Mechanismus der Gebirgsbildung," p. 68, 1878.

The relation of cleavage to stratification in folded regions is of first importance as a guide to structures that may often be obscure. Dale¹ has stated the facts very clearly, and we quote his summary, with the reservation, however, that it was written as applying to a specific case and that the particular conditions might vary in other localities. He says:

The rocks are all metamorphic and of few kinds, crystalline limestone, quartzite, and schists. The key to the structure is in the distinction between cleavage foliation and stratification foliation. The phenomena, as they occur on Mt. Greylock, involve cleavage, stratification and pitch of the axes of folds in a manner which led to the adoption of the following structural principles: I. Lamination in the schist or limestone may be either stratification foliation or cleavage foliation or both, or sometimes, in limestone at least, false bedding. To establish conformity (between strata) the conformability of the stratification foliation must be shown. II. Stratification foliation is indicated by: (a) the course of minute but visible plications (this criterion would fail in the case of cleavage foliation having been plicated, as happens in more intense or repeated folding); (b) the course of microscopic plications; (c) the general course of the quartz laminæ whenever they can be distinguished from those that lie in the cleavage planes. III. Cleavage foliation may consist of (a) planes produced by or coincident with the faulted limbs of the minute plications; (b) planes of fracture, resembling joints on a very minute scale, with or without faulting of the plications; (c) a cleavage approaching slaty cleavage, in which the axes of all the particles have assumed either the direction of the cleavage or one forming a very acute angle to it, and where stratification foliation is no longer visible. IV. A secondary cleavage, resembling a minute jointing, occurs in scattered localities. V. The degree and direction of the pitch of a fold are often indicated by those of the minor plications on its sides. VI. The strikes of the stratification foliation and cleavage foliation often differ in the same rock, and are then regarded as indicating a pitching fold. VII. Such a correspondence exists between the stratification and cleavage foliations of the great folds and those of the minute plications that a very small specimen properly oriented gives, in many cases, the key to the structure over a large portion of the side of a fold.

It is to be observed that the cleavage described by Dale is that which Leith calls "fracture cleavage" in distinction to flow cleavage. Such cleavage in some cases develops after the manner

¹ DALE, T. N., Mount Greylock, Its Areal and Structural Geology, U. S. Geol. Surv., *Mon.* XXIII, pt. 3, p. 125, 1894.

of minute thrust faulting in the overturns of the tiny plications, that is to say in the process of shearing that portion of the rock mass involved between the two passing limbs of a very small or microscopic fold. Again, there may be no apparent folding, even of microscopic dimensions, but displacement occurs on a plane of shear. And in related cases, where the recrystallization has gone far enough to produce a growth of mineral particles, oriented in parallelism, either as they formed or by rotation in the progress of the movement, the fracture cleavage partakes of the essential character of flow cleavage. This type of cleavage was distinctly recognized and described by Heim as "*ausweichungs clivage*." (Figs. 31 and 32.)

The most useful items in Dale's descriptions relate to the distinction of stratification and cleavage in foliated rocks, and further to the use of minute plications as indices to the character of the major structures.

SECTION II

CHAPTER VII

MECHANICS OF ROCK DEFORMATION

The Problem.—It is established by observation in all accessible lands that rocks, everywhere in the continents, have been broken, folded, sheared, squeezed, shortened, elongated, or made over, subsequent to their formation, consolidation, and hardening. All kinds of rocks have been affected in one way or another. The changes they have suffered are extremely variable. They are on a stupendous scale. The masses which have been moved are mountains or even parts of continents. The forces that have been and are now active are extraordinary. The time involved in accomplishing the changes is inconceivable.

While these things are true and superlatives are justified, it is equally true that the scale of effects in mountain growth is great only in relation to human standards. The mass of a mountain is insignificant in relation to the mass of the globe. The force required to fold a series of sediments several miles thick or to crush a thousand cubic miles of rock is inappreciable as compared with the weight of the globe. If we would estimate the phenomena in their true magnitude, we must consider them in relation to the magnitude of the earth.

It is known by observation that rocks bend without breaking, shear smoothly instead of breaking roughly, or undergo chemical changes and crystallize in ways which are different from those in which they break or react chemically at the surface, and it is inferred that the difference is due to the higher temperatures and greater pressures which exist at moderate depths beneath the surface, where the rocks were buried when the bending, shearing, or recrystallizing occurred.

It was long supposed that high temperature was the effective condition which enabled rocks to behave so differently from

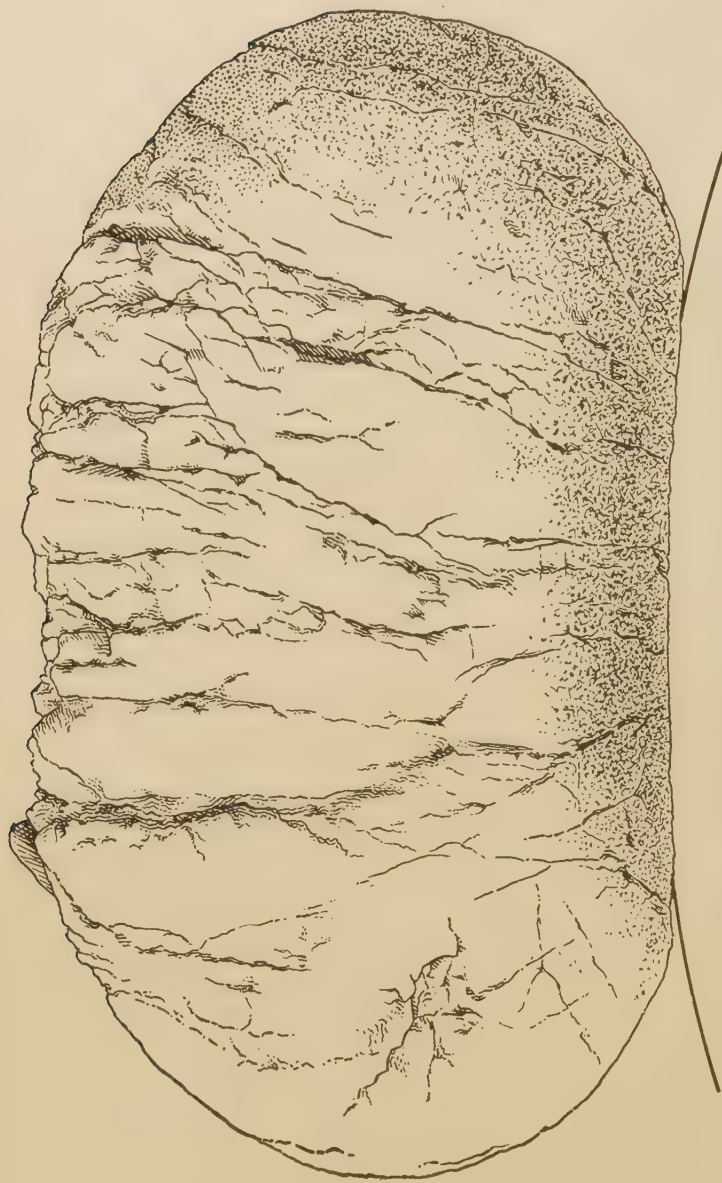


FIG. 79.—Drawing of a granite pebble, fractured by bending over another pebble.

Specimen from Eocene conglomerate involved in the San Andreas upthrust fault, near Loma Prieta, Santa Cruz mountains, California. The specimen shows the effect of bending and fracture by tension under moderate confining pressure. The pebble on the upper left hand was pressed into it. The lower surface of the bent pebble was flattened over the one on which it rested.

our common experience of them, and so far as chemical changes are concerned temperature is the more important factor. But the remarkable mechanical changes of form are now known to be made possible by the *confining pressure*, which, being exerted on all sides of a buried rock mass, holds it to a coherent whole, while an additional pressure from some particular direction forces it to change its form.

Finally, it is demonstrable that the mechanical principles which govern the action of breaking, bending, or shearing are independent of the magnitudes of pressures or masses involved, and therefore apply equally to the phenomena on the scale of the earth as to those which we can control.

The problem of structural geology is, therefore, to analyze the conditions under which certain known forces can have produced the observed effects in rocks of determinate character and in accordance with universal principles.

In the discussion which follows we take up in order

(a) the available forces, (b) the conditions under which the forces act upon the rocks at different depths in the earth's crust, (c) the mechanics of deformation at different depths as modified by the inherent qualities of different kinds of rocks.

Earth Forces.—The forces which we may invoke to account for the effects we observe in the structures of rocks and mountains are well known. There is no occasion or opportunity to call up mysterious, hypothetical attractions, such as the "magnetic or

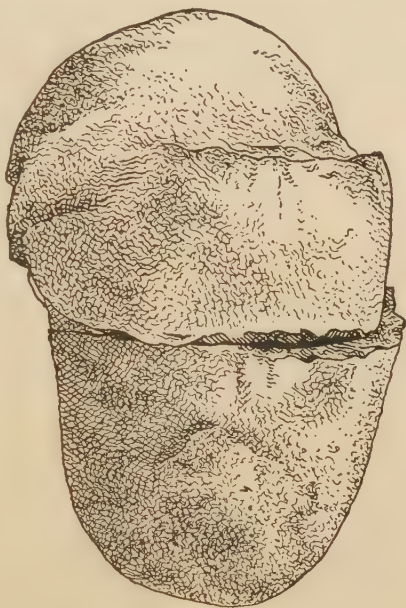


FIG. 80.—Drawing of a pebble which exhibits fractures that approximate the regularity of shearing, the matrix around the pebble having been in the zone of shear, whereas the pebble was in the zone of fracture. Cretaceous conglomerate, Alum Rock Creek, Mt. Hamilton Range, California.

polar " forces postulated by Sedgwick nearly a hundred years ago to account for the effects of temperature and pressure that result in cleavage. All of the phenomena of structures in rocks have been, or undoubtedly may be, explained by the action of forces in forms with which we are well acquainted.

There are two forces which are everywhere existent and always active or ready to act: gravity and molecular forces. The latter include adhesion, cohesion, and chemical affinity.

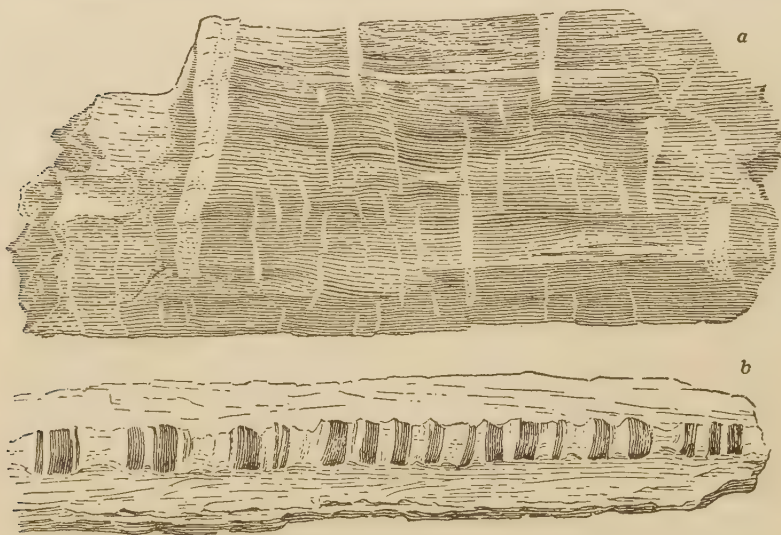


FIG. 81.—Illustrations of rocks which have been stretched by flowing. (After Heim, "Mech. der Gebirgsbildung," Plate XV.)

(a).—Tension openings or tears in clay-mica schist, "Thonglimmerschiefer," filled with calcite.

(b).—Segments of a fossil, a belemnite, separated by the extension or flow of the surrounding rock. The interspaces are filled with calcite.

They need no description or definition. They are alike in that they are known to us as attractions. Yet in relation to the structure of the rocks they play different parts, for gravity affects large masses and is effective because of the magnitude of the masses involved, whereas molecular attractions work in the infinitely small. Acting separately or together, they cover the entire scope of magnitudes, from the atom to the globe itself. These are the primary forces.

There are also two secondary agencies: pressure and heat. They are secondary because they are effects of the action of gravity or of molecular attraction, or of both. But in the study of rock structures we recognize them as causes, since we deal with the immediately effective force. The origin of that force is often obscure, for it may be either gravity or molecular force, or both, and it acts under conditions that may evade interpretation.

Pressure acts to move rock masses or to change their form, but only if it is unbalanced. Balanced pressure produces no effect, except one of compression. There must be unequal pressures, and the difference of pressure must be sufficient to do the work, if there is to be any movement or change of form. Heat also must be unbalanced, increasing or diminishing, if it is to effect a change from the state that has existed up to the moment of change. To express the fact of a difference of pressures or of temperatures we use the phrase *differential pressure* or *differential temperature*. And we may say that *the effective force which causes a change in rock structures of any kind is always differential pressure or differential temperature, or both*.

The list of available forces is not complete without the mention of the centrifugal force due to rotation, tidal stress due to external attractions, and magnetic forces. But the effects of these, in so far as they have any geologic effects, are outside of the subject of rock structures. The rate of rotation determines the shape of the spheroid, but not of its constituent parts. Tidal stress may have geologic effect, but only if its transient pull coincides with other conditions, as for instance, if it should release the hair trigger of an elastic earthquake. Magnetic forces probably do not have any effect in the solid earth. Thus we may leave these forces out of consideration as being entirely subordinate or negligible.

Static Conditions.—While it is true, as stated, that the changes which rocks undergo are the effects of differential pressures or temperatures, it is equally true that the kind of effect which is produced depends upon the static conditions of the immediate environment at the time of the reaction. To take a familiar illustration, water boils at a lower temperature on a mountain top than it does at sea level, because the air pressure, a static condition for the instant, is less in the former than in the latter environment. Similarly, it is necessary to understand the

environment of rock masses, that is to say the conditions of temperature and pressure to which they are subjected, at different depths in the earth.

Pressure and temperature both increase from the surface of the earth downward as far as observation penetrates, and there is no doubt but that the increase continues, though we cannot accurately estimate the rate, to the center of the earth. The uncertainties of our knowledge do not, however, materially affect that outer zone in which the structures we have to consider are developed—a thin outer skin, as it were, ten to twenty miles deep. For this external shell we may reasonably accept the rates determined from superficial observations.

Pressure, which is due entirely to the weight of rock resting on a buried mass, increases as we go downward directly with the depth. If the weight of a cubic foot of rock be taken at 175 pounds (specific gravity 2.8), the pressure on each square inch of the base is 1.22 pounds. This is for one foot high and by multiplying we get a pressure of 6,400 pounds per square inch at a depth of one mile. At this rate the weight resting on a rock surface one inch square at a depth of twenty miles is 128,000 pounds. The crushing strength of the strongest rocks at the surface is about one-fifth of this enormous pressure. Hence we may conclude that the rocks at some distance beneath our feet are potentially crushed; that is to say, they would crush if they were not held together by lateral pressures. This is the most fundamental concept of structural mechanics. It was first recognized by the Swiss geologist, Albrecht Heim,¹ who founded upon it his theories of rock deformation.

We cannot, however, directly calculate the depth at which any particular rock of known strength would crush, because another effect of great pressure is to strengthen rocks. The zone of potential crushing lies deeper, therefore, than we might guess. (See pages 135–139.)

The internal heat of the earth is derived from the compression of the interior under the weight of the outer portion. It is thus an effect of gravity. The temperature is very high in the interior and is lowest at the surface. By observations at accessible depths it has been determined that going from the surface toward the interior there is a normal rise of temperature of 1

¹ HEIM, ALBRECHT, "Mech. der Gebirgsbildung," 1878.

degree Fahrenheit for every 60 feet of added depth. According to this the melting temperature of rocks at the surface would not be reached above a depth of 25 miles, and, in view of the fact that melting points are raised by pressures, it is altogether probable that the normal temperature of the earth is below the melting point of rocks at all depths. This view is in harmony with the many facts that demonstrate the solidity of the earth. We are thus prohibited from assuming that rocks are materially weakened by heat, except where local conditions may raise the temperature above the normal for any particular depth.

Dynamic Conditions.—The normal conditions of pressure and temperature, supposed to exist at increasing depths below the surface of the earth, may be regarded as constant for the epoch corresponding to any displacement of mountain masses. They are static in the sense that any change in their intensities is imperceptible. We are thinking now of general changes, such as those which might be involved in the contraction of the globe. It has been a widely accepted theory that contraction due to cooling is a cause of mountain uplift, but the two processes are incommensurate. In the hundred million years or more of the legible geologic record there has been no recognizable shortening of the earth's diameter, whereas there have been many episodes of mountain growth, any one of which may have been accomplished in one or two million years. The time ratio is as one hundred to one, or is even more disproportionate.

Pressure due to gravitative stress can change only by removal or addition of load or by a change of density, or both. Any such process is exceedingly slow as compared with deformation. Hence we have described the normal pressures and temperatures as static, in the sense that they are relatively constant.

Nevertheless, the evidences of movement noted in rock structures are so numerous and on so large a scale that it is clear that dynamic conditions exist from time to time; that is to say, conditions of very active movement. These require the development of unbalanced forces and, since rocks are exceedingly rigid and exceedingly strong, these unbalanced forces must be very great.

The origin of these stresses is a matter of hypothesis, which it is not necessary to discuss in order to understand the mechanics of their action. The mechanic does not need to know the chemical reaction which releases the molecular activity of the gasoline to

know how the latter drives the automobile. In what follows we consider chiefly the recognized facts of the existence and nature of the unbalanced forces.

Rocks everywhere exhibit the effects of crushing. We see the crevices. The agents of weathering, heat and moisture, discover them when they are still too fine to be seen by the eye. They divide rocks into small blocks. It was found impossible to secure flawless columns 60 feet long for the Cathedral of St. John the Divine in New York, even from the most massive granite mass known in New England. The cliffs of the Yosemite show innumerable shearing planes traversing the great granite mass. Yet granite is the most massive of all rocks. The study of the mechanics of these shearing planes demonstrates that they are effects of very great unbalanced pressure.

Sedimentary strata are known to be laid down originally in flat layers, in a nearly horizontal position. But they are found tilted up and bent double upon themselves. The mechanical analysis of the phenomena shows that they have been subjected to pressure exerted in the direction of the bedding with sufficient force to fold them. As the masses of strata thus folded range in thickness from 10,000 to 30,000 feet, the unbalanced pressure must have been very great. Its initial direction must also have been nearly horizontal.

Many dislocations of the earth's crust are demonstrated by comparison of the masses on one side of the break with their equivalents on the other side, and it has been shown that the segments of the crust thus moved are of the magnitude of mountain chains. Mountains or mountain ranges have thus been thrust 10 or 20 miles from their foundations. The displacements are essentially horizontal in direction and the pressure must have been capable of shearing through the foundations as well as of moving the masses.

It is demonstrable by observation in the large as well as under the microscope that very large bodies of rock, bodies of sub-continental dimensions, have been squeezed thin and correspondingly elongated to several times their original length. The force required thus to affect the intimate internal structure of the mass is even greater than that necessary to move it from its base. It was, moreover, an unbalanced pressure, since the minerals are lengthened in a definite direction, the direction of least resistance.

The groups of facts enumerated are all observed at the surface, but the rocks are known to have been uncovered by erosion and to have risen to the surface from greater or less depths. The structures from which we deduce the existence of dynamic stresses are of a character which could not be produced under surface conditions. They have developed at a considerable depth beneath the surface. Hence, we are justified in concluding that there are conditions which from time to time evolve and bring into play stresses of a temporary character, but of very great power, and that these stresses originate at depths of several miles below the surface of the earth, where they produce dynamic effects.

Summary Regarding Forces.—From what precedes we may conclude that the agencies which affect any rock mass in the processes of deformation are gravity, heat energy, and molecular attractions, together with such resultants of any of these, singly or in combination, as may develop from local mechanical or physical conditions.

Furthermore, since the activities of deformation are not continuous, but are renewed from time to time, it is evident that the effective forces include a variable, to whose waxing or waning the alternations of movement and quiescence are due. The dead weight does not possess this characteristic, even though it be so great as to develop in the rocks a state of potential crushing. Molecular attractions are in equilibrium, so long as the pressure and temperature conditions are stable. The intensity of heat energy is, however, subject to variation, not in its source presumably, but in its conduction and accumulation. And it is probably through this variable that the potential energies of the molecular and terrestrial gravitations are set loose, in such a manner as to produce deformation of the rock masses.

Mechanical Characteristics of Rocks.—Rocks as we know them at the surface are hard, inflexible, brittle, the very symbol of rigidity. Only in very thin layers can we recognize any flexibility. Only some very fine, soft clay rocks exhibit plasticity. To say that a rock will flow is to use words which contradict one another. Nevertheless, the student of mountain structures is forced to recognize that rocks will bend without breaking and will even flow, provided that they be buried deep enough in the earth's crust, for he observes that they indubitably have done so.

The initial suggestion is that the rocks were still soft when they were deformed. We know that wet clay can be forced into the form of a mold or through a pipe, and we reason by analogy that rocks of various kinds may have been put through some similar process while still soft. But the analogy will not stand analysis and the deformed rocks themselves present facts that contradict the assumption. For instance, in a succession of strata we may find pebbles of an older rock in a later conglomerate. It is evident that the older stratum was already hard when the younger was deposited. And yet both strata may have subsequently been folded without breaking. Or an ancient limestone, even a very hard, flinty one, may have been bent during a comparatively recent episode of deformation. There is no question but that the flinty limestone would have been as brittle when folded as it now is, if it had been surrounded by the same slight confining pressure. A critical investigation of the age of rocks at the time they were deformed shows that in general they were so seasoned to resist stress that they must be regarded as having attained their ultimate strength under the environment in which they were buried.

Rocks are strong. That is to say, they can resist unequal pressures up to a large difference. When we put a cube of rock in a testing machine it is surrounded by the balanced pressure of the air. We apply a definite force in one direction, an unbalanced pressure, and we observe that the amount of pressure required to crush the rock is large, as our measures go; 10,000 to 30,000 pounds to the square inch. The rock is strong when surrounded by the universal air pressure, 14.7 pounds to the square inch.

Now let it be assumed that we can increase the air pressure indefinitely and under such conditions that the pressure will be exerted on all external surfaces of the rock mass, but not internally. It may then be called a *confining pressure*. The particles of the rock will be pressed closer together. Will the rock thereby be rendered stronger or weaker? This is a crucial question in relation to the theory of rock deformation and movements of the earth's crust.

Let the confining pressure be raised to 30,000 pounds, equal to the crushing strength of the strongest rocks under the pressure of the atmosphere alone. Will the rock be crushed? No, confining pressure which acts equally on all external faces cannot

crush a solid, in the sense of breaking it down. It can compress it, but to the extent that it does so it forces the particles into closer relations and reduces their freedom of movement. A rock is thereby made stronger.

Experiments by Adams¹ demonstrate that granite under a confining pressure of 26,000 pounds to the square inch is four times as strong as when subjected to atmospheric pressures alone. The increase of strength is attributable to the greater internal friction developed by the restraint imposed upon the movement of the particles. Continued to higher pressures the experiments showed that the strength rises with the rise of confining pressure, though at a diminishing rate. They gave no ground whatever for the assumption that any such pressure, however excessive it might be, could make rocks soft.

Hence, it follows that the rocks which were bent or sheared at depths in the crust where they were subjected to great confining pressures were materially stronger than they are when exposed at the surface. The unbalanced pressure required to move them was, therefore, much greater and was proportionately greater as they lay deeper.

The effect of load upon the strength and manner of yielding of rocks is so surprising that we may well give it further consideration.

The weight resting upon any rock mass which is buried in the earth depends upon the depth at which it lies and increases with the depth. We know from tests of the crushing strengths of various kinds of rock, when surrounded only by the confining pressure of the atmosphere, that if they could be obtained in masses free from flaws they would support rock columns 8,000 to 25,000 feet, or one and one-half to five miles high. For height we may substitute depth, but we have then to consider that rocks grow stronger with the increase of confining pressure, that is with the increase of load.

Here the rate of increase of load as compared with the rate of increase of strength comes into the problem. If the load increases faster than the absolute strength, the relative strength

¹ ADAMS, F. D. and BANCROFT, J. A., On the Amount of Internal Friction Developed in Rocks, *Jour. Geol.*, vol. XXV, 1917.

WILLIS, BAILEY, Discoidal Structure of the Lithosphere, *Bull. G. S. A.*, vol. 31, 1920.

will become less. The load gains a little more than in direct proportion with the depth. The absolute strength due to the confining pressure grows at first faster than the depth and then at a decreasing rate, as may be seen by a study of the hypothetical curve *LMNPQR* given in Fig. 82, deduced from Adams' experiments.¹

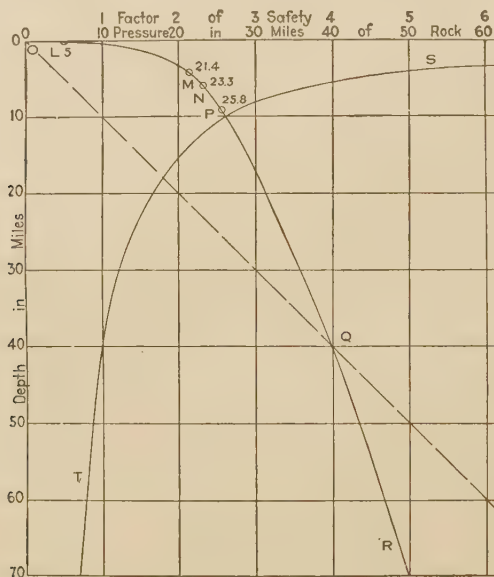


FIG. 82.—Comparison between the actual strength of granite and the load on it at different depths in the earth's crust.

The curve *LMNPQR* represents the crushing strength in miles of rock. The broken line *OQ* represents the actual load. The ratio between the two, or factor of safety, is shown by the curve *ST*. At a depth of 40 miles, at *Q*, the load equals the crushing strength, and the factor of safety is 1. At greater depths the rock is potentially crushed.

The distinction between absolute and relative strength may, at first thought, seem strange, but it is a necessary consideration in designing any structure which is to carry load. The absolute strength is measured by the unbalanced pressure under which the material will fail and, as we have seen, it varies with the confining pressure. The relative strength is the ratio between the absolute strength and the actual load. To obtain it we divide the absolute strength by the load. It is the factor of safety.

¹ WILLIS, BAILEY, Discoidal Structure of the Lithosphere, *Bull. G. S. A.*, vol. 31, 1920.

At the surface the factor of safety of a rock, having a finite strength and being under no load, is infinity. At a depth of 4 miles the factor of safety is about 5 and at 6 miles it is about 4, as shown by Adams' experiments. By hypothesis it diminishes to 1 for the strongest rock at a depth of 40 miles, at surface temperature, as shown by the curve *ST* (Fig. 82). In this paragraph we may substitute the term relative strength for factor of safety, throughout.

Hence we conclude that, at a depth of about 40 miles below the surface, the relative strength of the strongest rock is 1, that is, the absolute strength is just equal to the superincumbent load. Weaker rocks must be similarly conditioned at less depths. And any rock at a depth below that at which its relative strength is 1 has a factor of safety which is a fraction. This means that the *confining pressure exceeds the absolute crushing strength*.

Let us consider what degree of stress will cause movement under these conditions. If the confining pressure remains constant on all sides, the rock will continue to have the corresponding absolute strength and any unbalanced force, to cause movement, must rise in intensity to the point where it is more than equal to that absolute strength. If the confining pressure be partially relieved on one side, the absolute strength will diminish correspondingly and the requisite deforming force will be less, in proportion to the reduced absolute strength. If the confining pressure were entirely removed, the rock would retain only the strength it has at the surface. If the confining pressure be indefinitely increased, the absolute strength will also rise, though not in the same proportion.

The condition of a rock which is under a load such that the relative strength in that environment is 1 or less than 1 may be described by the phrase *potentially crushed*. The idea is an unfamiliar one and is not accurately represented by any term in general use. The word *plastic* is employed, and there is nothing better to suggest the manner in which the material yields to a sufficient stress. The wax or clay or steel or rock is plastic. It will yield without breaking. But we must be careful to exclude the notion of *ease of movement* which the term connotes. Plastic rock, confined at a depth of, say, 40 miles beneath the surface under a universal pressure of 250,000 pounds to the square inch, is not soft. It is much harder and requires an enormously greater

pressure from one side to move it than would be necessary at the surface.

In applying these considerations to the study of the mechanics of deformation we must bear in mind that the discussion has dealt with static pressures due simply to load. Where there is movement in progress the dynamic conditions of stress may locally greatly exceed those which would be implied by the depth below the surface, and this fact, combined with the variation in the strength of rocks, suggests how it is that folding and distortion have occurred without fracture at relatively moderate depths.

Effect of Heat versus Pressure.—The preceding discussion was made without reference to the question of temperature, because the rocks which have been folded or faulted do not, as a rule, show the effects of heat. They have not been hot enough to become pasty or liquid. Nevertheless, they have been at temperatures such that they must have been expanded to some degree, and this expansion must have offset, to some extent, the effects of compression, considered in the previous paragraphs.

The effects of expansion and compression to be discussed are within the elastic limit of the rocks; that is, they are changes of volume or of form from which the rock will recover elastically, if the preceding condition of heat and pressure be restored. We are thus considering effects of a different and much smaller degree than those hitherto discussed.

Compression due to confining pressure and expansion due to rise of temperature are opposed. The one forces the molecules closer together, the other spreads them apart. Both pressure and temperature increase with depth. Their relative effects depend on the relation of their rates of increase, and it were possible to assume that rocks might grow denser through excess of compression, or might remain unchanged in volume because of a balance between compression and expansion, or might grow lighter on account of a more rapid rise of temperature.

It is regarded as well established that there is an increase of density from the surface downwards in the earth and consequently that the effects of confining pressure overcome those of rising temperature, under normal conditions. Compression advances more rapidly than expansion. We cannot entirely omit from consideration, however, the effect of heat, and it is, therefore,

not possible to deduce the actual strength of rocks in the earth's crust from experiments conducted under conditions of uniform, low temperature. The conclusion of the last section holds in spite of the effect of heat, but to what degree we cannot state with exactitude.

The equilibrium between the effects of heat and pressure is maintained by the elastic activity of the rocks, and this has an effect upon their liveliness which removes them from the class of dull, lifeless things they appear to be. If they lie at depths beyond five miles, or even less, we must consider them as being under a confining pressure sufficient to hold them firmly together in all their parts, yet subject to increase of volume through change of temperature. Compression and expansion wrestle with one another in constant and unrelaxing opposition. If pressure lessens, expansion instantly ensues. If temperature falls, compression immediately takes place. The rock responds at once to the slightest change in the conditions of its environment by a corresponding change in volume.

Although the normal rise of temperature as depths within the earth increase is inadequate to overcome the effects of the more rapidly growing pressure, there are exceptional developments of high temperature which do offset pressure and result in momentous reactions. The cause of these special conditions is a matter of hypothesis.¹ It may probably be found in irregularities of conduction, by virtue of which heat energy, flowing more rapidly from the highly heated interior than through the less dense outer shell, especially in rock masses of high conductivity and low specific heat, accumulates to a degree sufficient to cause recrystallization or melting. In consequence of these effects it then becomes latent, and in the case of melting may be carried out by the extrusion of the molten mass. The condition of high temperature is thus both local and temporary, and in this respect the hypothetical occurrence corresponds with that which is demanded by geologic evidence of variations in the activity of mountain growth and volcanoes.

The intensification of heat energy is a direct cause of metamorphism and igneous activity and, moreover, brings into action those very powerful molecular forces, which presumably are the ultimate forces that move mountains. The theories

¹ CHAMBERLIN, T. C. and SALISBURY, R., "Geology," vol. 1, pp. 559-569, 1909.

which prompt this statement are outside the scope of this volume.¹

Kinds of Deformation.—In what follows it is necessary to use familiar words with somewhat special senses, and we must clear the way by explaining them. In speaking of the distortion of rocks we distinguish fracture, fold, shear, and flow, all simple words, but words not always used in the same sense by different writers and therefore a cause of fruitless controversy. In this work they are used with the meanings and implications stated below.

A fracture is an open break. The term carries with it the idea of a separation of the parts into which a mass or particle has been broken. Size is not an item in the definition. Fractures may be miles in length, thousands of feet deep, and proportionately wide; or they may be microscopic in all dimensions. At the time of the breaking, the fracture opened. Whether it be immediately or subsequently closed, the closing none the less followed opening.

A fracture is a rough break. The direction and the details of the surface of fracture are determined by the internal strength and resistances of the material fractured. In these respects fracture is distinguished from shear, but as will appear shear may develop from fracture or may disperse into fractures.

A fold is a bend. Only bedded rocks and laminated rocks can be bent without fracture and the term fold is therefore limited to the forms which they take. The degree of folding does not enter into the definition. A gentle flexure is therefore a fold, as is also a closely compressed crease. The definition cannot be limited by the mode of action of the forces to which a fold may be due. They may act in a horizontal or vertical or inclined direction, parallel to or across the strata, but if the strata are bent the structure is a fold in any case. In this respect the term folding is broader than that of warping, which is a deflection due to vertical forces, and fold is more comprehensive than upwarp or downwarp.

¹ WILLIS, BAILEY, Research in China, Carnegie Institution of Washington, *Publication* 54, vol. 2, pp. 130-131, 1907.

BARRELL, JOSEPH, The Strength of the Earth's Crust, *Jour. Geol.* vol. XXII, p. 428, 1915.

WILLIS, BAILEY, Discoidal Structure of the Lithosphere, *Bull. G. S. A.*, vol. 31, p. 270, 1920.

Folding requires both the extension and compression of rocks and can take place, therefore, only under those conditions where these reactions are possible. Extension and compression require, however, either fracture or shear or flow of the rocks involved, and folding can therefore occur only where one or two or all three of these phases of deformation may take place.

Shear is a smooth cut. It is that kind of a parting of a mass which is produced when the blades of a scissors pass one another in opposite directions. If they be close together we get a clean cut. If they be not very close, the material between them is turned to one side, is rotated and laid more or less nearly parallel with the shear. Shear is therefore associated with rotation, but in rocks the film in which rotation occurs is often so thin that the parting appears as a smooth plane. When this is not the case, the laminae between the gliding masses are bent in toward the central plane and torn apart. Thus, shearing and folding are associated.

Shear is produced by a couple of external forces and bears a definite mathematical relation to the direction of the major differential stress, which causes deformation. The possible planes of weakness in the material subjected to shear may affect the direction of the planes so that the mathematical relation is modified. The shear may thus be diverted into planes in which it would otherwise not take place, or it may be rendered irregular and become a fracture. There is, however, a sharp distinction to be made between deformation by fracture, which is directed by the weaknesses of the rock, and deformation by shear, which is controlled by the intensity of external pressures. This distinction cannot be appreciated in all its significance without a discussion of the relation of fracture and shear to the confining pressures, which is given in the analysis of the conditions that govern each mode of change of form.

Flow is a change of form without apparent rupture. It will be shown that the appearance is probably nothing but a question of scale and that flow is sub-microscopic or molecular shear. We detect under the microscope shearing which escapes our unaided eye but which obeys the laws that distinguish shear. Those laws are independent of size, and it is reasonable to infer, though not now possible to prove, that they govern the form of displacement which we know as flow. Flow and shear appear to be intimately

related, if not the same mechanical effect. Flow involves, however, the development of new minerals, at least in those cases where it is most perfectly developed, and it is a term which will be used with that implication, even though it also carries the idea of microscopic or sub-microscopic shear. Flow, like shear is controlled by the external forces rather than by internal resistances.

Zones of Deformation.—It has become customary to speak of a zone of fracture, a zone of flowage and fracture, and a zone of flow, as existing in the lithosphere. One may also name a zone of folding, a zone of shear, or a zone of recrystallization. These are convenient descriptive terms with which to indicate the predominant type of deformation which has developed in a certain structure. They are, however, inexact and may be misleading, since more than one type of deformation commonly occurs in any part of a structure.

Heim,¹ the founder of modern structural geology, laid down the following principles:

(a) Deformation without fracture occurs in a very similar, or even identical form in rocks of very unlike character, in more plastic or more brittle rocks. Deformation without fracture is not related to any kind of rock. (b) Rocks of the same kind and belonging to the same strata, which have been deformed by breaking in one place, occur elsewhere folded without fracture. (c) Deformation with fracture and without fracture may occur in one and the same piece of rock.

Van Hise, to whom we owe the formulation of the principles of structure in their present accepted form, put the definition of zones in the following terms:²

In the placing of a rock mass in one of the three zones it is to be considered as belonging to the one to which it most closely corresponds. If the rocks are everywhere broken and show but little folding, they are in the zone of fracture; if they show much fracturing and also are folded, they are in the zone of fracture and flowage (folding); if the fractures are subordinate or microscopic, they are in the zone of flowage (shear or recrystallization).

The works of Heim and Van Hise were founded on exhaustive studies, concerning in the former case the rocks of one of the most

¹ HEIM, ALBRECHT, "Mech. der Gebirgsbildung," vol. 2, 1878.

² VAN HISE, C. R., "Principles of North American Pre-Cambrian Geology," pp. 602-603, 1896.

complicated districts of the Alps and in the latter the ancient rocks of the pre-Cambrian. They include therefore phases of intense deformation and phases of very deep-seated deformation. It will be noted that fracture is a mode of change of form in both classes of structures.

When we speak of the zone of fracture as contrasted with the zone of flow, the implication is that the former is superficial and the latter is relatively deep below the surface. Now it is true that a soft wet clay will break if bent sharply under little or no load. The zone of fracture therefore does begin at the surface and includes the softest materials. But at a very slight depth such a mass is obliged to change form by plastic flow without breaking; that is, the zone of fracture is very shallow, the zone of flow by shear lies very near the surface—for wet clay.

Quartz, one of the hardest and most brittle rocks, is of course in the zone of fracture when deformed under any but very great confining pressure. It is not in the zone of flow where most other rocks are; indeed Van Hise describes fractured quartz grains in strata of quartzite folded upon themselves without fracture and, in that case, it is rather a question of the magnitude of the mass deformed than of the kind of material. For quartz the zone of fracture may thus be said to be as deep as the greatest depth from which rocks have been raised to the surface.

Again, it is to be noted that the static pressures due to load may be greatly exceeded, locally, by stresses accumulated or intensified in the development of a fold or thrust fault or other large structure, and thus the local stress under which a rock may be deformed may become much greater than that which would be indicated by the depth of the mass below the surface.

All of these conditions: diversity of rock resistance, inequalities in the degree with which a large mass or a small particle is pervaded by the confining pressure, and differences in the intensity of local stresses, tend to modify the influence of depth upon the character of deformation. It follows, therefore, that the term zone can be used only with reservation and is not to be interpreted as meaning that the lithosphere consists of fractured, folded, or sheared shells, one below the other. The two extremes, fracture and flow, overlap throughout what we may designate the zone of observation.

While the above generalization is true, especially from the

point of view of detailed petrographic study of the characteristics displayed by rocks which have been deformed, it is also true that in a broad way it is convenient and instructive to recognize the superposition of the zones of deformation. The zone of fracture is best developed from the surface down to a depth of 5,000 feet

ZONES OF DEFORMATION

Zone of Fracture Surface	Zone of Competent Folding Surface	Zone of Shear or Mechanical Flow Surface	Zone of Recrystallization or Molecular Flow Surface
Extends from the surface down, fractures growing smaller.	1,000 ft. Does not usually occur above one thousand feet.	3,000 ft. Does not usually occur above three thousand feet.	
5,000 ft. Becomes microscopic below five thousand feet.			5,000 ft. Does not usually occur above five thousand feet.
Vanishes into the depths where even microscopic fractures cannot open. Probably does not extend below 30 miles.	Does not usually extend below 30,000 feet. Replaced by shear.	Extends to an indefinite depth, until replaced by the conditions of local recrystallization or fusion.	Extends to the zone of local fusion or to an indefinite depth.

or more. It continues to 20,000 feet or more as an appreciable structure, but diminishes to a microscopic scale. Theoretically it may extend to a maximum depth of 150,000 feet or 30 miles. The zone of folding, more especially that type of folding which is called competent, does not rise to the surface, although it may approach it within 1,000 feet, and it probably does not extend below a depth of 30,000 feet or 6 miles. The zone of shear or mechanical flow may approach the surface within 1,000 feet, as folding does, but

it goes to much greater, indeed to indefinite, depths, shear being probably the mode of mechanical deformation at the greatest depths at which solid rocks are deformed in the earth's crust. Flow by recrystallization, involving the chemical reactions incident to solution and redeposition of the same or of new minerals, may occur with folding, possibly at depths of the shallowness of 3 miles, and is an associate of shear at all depths. It may also occur independently of shearing, under static pressures, provided the conditions of temperature change in such a way as to promote chemical reaction.

The grounds on which these depths are limited are given in connection with the statement of the mechanical analysis of each phase of deformation.

Analysis of Fracture.—Fracture, as the word is used in this work, means a rough break. It is distinguished from a shear, which is a smooth break. When a substance fractures, the adhesion or cohesion existing between the particles is broken and they are so separated that they no longer adhere. The direction of the fracture may be controlled in some measure by the blow or pressure, but the internal resistances or weaknesses are influential and in determining the details of the broken surface they are dominant.

A conglomerate breaks around the pebbles, a sandstone around the grains, a shale along a parting in the clay, a limestone or glass with a conchoidal fracture determined by the elastic vibration of the material.

Ordinarily, we are not concerned with the external environment of the material. The surrounding air pressure is negligible. But when substances are under greater pressures they can part only in case they are strong enough to bridge any opening which the parting may produce. Hence, the greater the general pressures, the stronger must be the material in order that it may fracture.

Bridging implies an opening and an open space is characteristic of fracture. The space may be round or flat, large or small; it may be an open fissure, such as is filled by a vein, or a crack in a sand grain. In all cases the idea of fracture implies an open space, separating the walls beyond the radius of attraction of adhesive or cohesive forces and remaining open an appreciable time.

The forces involved in fracture are three: an unbalanced force which causes the break, the inherent strength of the material

which resists it, and the balanced confining forces which aid the resistance. If fracture occurs the first must be enough greater than the other two to separate the pieces.

If we consider what forces are active at the surface or near it to cause fracture, we find that they are due to changes of temperature, the mechanical or chemical activity of water, or localized effects of gravity. Temperature changes of rocks disrupt them because the different mineral constituents expand and contract unequally. Water, freezing in crevices, breaks the blocks apart. Moisture, entering into combination and forming hydrated minerals, causes the altering material to expand and exert great pressure. Gravity may be localized by a weakening of the resistance opposed to it, as when water percolating on a seam lubricates the surface and reduces friction, or when in the progress of earth movements a mass becomes unbalanced and throws its weight on one side. None of these effects can be regarded as a major incident of rock deformation. They occur only where the absolute strength of the rock is weakest and where the confining pressures are least.

Beneath the surface fracture may be occasioned by the vibrations of an earthquake shock or of a volcanic eruption, within the areas of such activities. The more general cause, however, is the bending or displacement of masses where the unbalanced stresses are sufficient to produce movement, but the confining pressures are not adequate to force the rock to shear. Fracture is therefore a common associate of folding and faulting.

Heim¹ investigated the relations of fractures to folds and described them minutely as they occur in the great overfolds of the Alps. His description has general application and may be summarized as follows: the great arches of the major folds seem to have been developed without breaks, but on examination it is found that they are traversed by many veins of quartz or calcite. Since the sides of any vein would fit together, if the vein matter were removed, it follows that the veins are equivalent to older, open fissures. He observed that the number of veins increased with the sharpness of the folding in the same stratum and locality. With reference to the occurrence of fractures in different parts of a fold, it is observed that within an arch, where the strata are under lateral compression, there is extension in the direction of the radii.

¹ HEIM, ALBRECHT, "Mech. der Gebirgsbildung," vol. 2, pp. 12-31, 1878.

Hard, brittle rocks, which because of their hardness were in the zone of fracture, may there be torn apart in the direction of the radii, where softer rocks suffer plastic deformation. Such structures are characteristically irregular. On the outside of an arch, on the contrary, the stretching of the strata in bending produces a tension-stress which may cause a strain in the direction of the tangent, with the result that fissures, proportionate in number and size to the acuteness of the bend, develop at right angles to the tangent and generally parallel to the axis of the fold. They will be parallel to the strike of the beds only if the axis of the fold is horizontal.

By detailed measurements Heim determined that the total spaces represented by the fissures corresponded fairly well with the amount of stretching demanded of any individual bed, but if greater thicknesses were taken into account there was a marked deficiency. He thus demonstrated that the beds had not bent as one bed, but each one for itself, and the excess of stretch required by the whole thickness had been adjusted by slipping of the strata on one another. This is one of the principles of adjustment in folding.

In case the bending of strata takes such a form that there is a torsional strain, conjugate joints may be developed, as is explained under jointing, and these may become open fissures in one or both directions. The mass of a stratum may thus be separated into detached blocks.

In general it is to be said of deformation in the zone of fracture that it is governed by the lines or surfaces of weakness in the rocks. The rock itself, being by hypothesis stronger than the stresses produced by the confining pressure, is not strained beyond the elastic limit before the mass yields along a plane of inherited weakness, a surface of stratification, bending, shearing, or cleavage. The forces which may act upon any mass in the zone of fracture are resolved into components perpendicular and parallel to the external surface and thus cause movements or breaks in directions controlled by the block itself. Stresses directed by deep-seated movements may be sharply diverted or dispersed, and their expression at the surface may differ from their original orientation. This applies, however, to the displacement of relatively small masses on fracture planes. *Large masses, such as mountain chains, are moved by deep-acting pressures, which are*

beyond the effect of surface conditions and direct the surface expression in a large way.

Analysis of Competent Folding.—Folds of very similar character may be produced by horizontal compressive stresses or by vertical forces or by a combination of the two. As a rule, however, the structures which are studied as folds, comprising anticlines and synclines and associated thrusts, are due to compression. They will, therefore, be discussed first under the head of that type of folding which is produced by horizontal stress, namely competent folding.

Competent folding is that folding of strata which is produced by compression in the direction of the undisturbed stratification, and which is conditioned by the requirement that a rising arch shall lift the load, or a sinking syncline shall displace the underlying material.

The usual condition is that the strata assume initially a nearly flat, horizontal or gently inclined attitude, in course of the subsidence which accompanies deposition. They consolidate. They may become jointed at right angles to the bedding in consequence of the warping or twisting due to subsidence. In course of time, it may be after long ages, they are subjected to compressive stress in the direction of the bedding. A fortuitous coincidence of the direction of force with the direction of bedding need not occur, for if the force makes a small angle with the bedding it will develop a powerful component in the plane of the latter and the effect will be the same as if the original stress had that relation.

Under these conditions a stratum is a strut, which is subjected to the shearing and bending stresses incident to its mechanical situation. If it be short and stiff, it may shear before it can bend. If it be rigidly supported below and confined by a sufficiently heavy load above, it also may shear before it can bend. But if it be of considerable extent in comparison with its thickness and be not too rigidly restrained above and below, it will bend rather than shear.

It is reasonable to assume that strata usually, if not universally, bend upward more easily than they can bend down, because the overlying load may be lifted into the air, whereas the foundation would have to be forced into the globe. Bending thus implies up-arching and up-arching implies lifting the load.

The load consists of the weight of the stratum itself and the weight of any superincumbent strata which do not lift them-

selves. It is possible to conceive a sequence of beds so nicely adjusted as to strength and flexibility that each one could just lift its own weight and would thus act independently of any of the others. But such an adjustment would be a surprising accident. In nature rigid sandstones are commonly associated with flexible shales. Strong, massive limestones are interbedded with thin-bedded strata of limestone and shale or sandstone and shale. The differences of flexibility and strength are very pronounced and the sequences very diverse. Weak beds are often *incompetent* to lift any appreciable part of the confining pressures. They perforce move passively. Strong beds, on the other hand, are *competent* to move the passive beds and carry up the weight of overlying strata. Up-arching can occur only when there are strong beds, competent strata, capable of this lifting. This kind of folding is therefore called *competent folding*.¹

In order that any stratum shall be competent it should possess certain inherent characteristics in a degree superior to that in which they are possessed by other strata. These qualities are (a) strength to resist shearing; (b) capacity to heal fractures; (c) inflexibility. On the other hand, the conditions which favor incompetence of strata in folding are (a) lack of coherent strength; (b) lack of cementing quality; (c) flexibility.

We may consider various kinds of sedimentary rocks with reference to these qualities.

Limestone is one of the strongest of the sedimentary rocks.² Tests for crushing strength at the surface show a range from 11,000 to 30,000 pounds to the square inch. It is strongest in the metamorphic, crystalline varieties, and it shares the quality of great strength with slate. The strength may be attributed to the fineness of grain and the consequently numerous points of contact between the grains in unmetamorphosed limestone, and this effect is increased by the cementing action of calcite in the marbles.

Limestone heals readily. If a break occurs, the soluble substance of the rock itself cements the fissure and the cemented plane approaches or may exceed the original rock in strength. No non-

¹ WILLIS, BAILEY, "Mechanics of Appalachian Structure," p. 247.

² Adams found the following relations of strength, as expressed by the "work done" in compressing cylinders of various rocks in confinement. (See the paper on the Amount of Internal Friction Developed in Rocks During Deformation, *Jour. Geol.*, vol. XXV, p. 630, 1917.)

calcareous rock has this quality in equal degree in the zone of folding.

Because of its great strength and because it usually accumulates in relatively thick, undivided beds, limestone is inflexible. It does not bend readily. When forced to bend it does so in major folds, in long curves, which conform to a uniformly distributed stress and consequently distribute the deformation in

RELATIVE AMOUNT OF WORK DONE IN EFFECTING AN EQUAL DEFORMATION IN UNIT COLUMNS OF DIFFERENT ROCKS.

	Under Resistance of	
	0.25 cm. Steel Tube	0.33 cm. Steel Tube
Steatite.....	26,054	34,123
Alabaster.....	35,569	42,946
Sandstone.....	41,262	53,446
Marble.....	51,708	60,415
Dolomite.....	66,362	77,092
Belgian Black.....	73,754	79,362
Slate.....	79,069	97,154
Diabase.....	92,985	107,431
Granite.....	104,169	119,877

If the work done to deform marble be taken as unity, these figures may be set forth as in the following table:

	Under Resistance of	
	0.25 cm. Steel Tube	0.33 cm. Steel Tube
Steatite.....	0.50	0.56
Alabaster.....	0.69	0.71
Sandstone.....	0.80	0.88
Marble.....	1.00	1.00
Dolomite.....	1.28	1.28
Belgian Black.....	1.43	1.31
Slate.....	1.53	1.61
Diabase.....	1.80	1.78
Granite.....	2.01	1.98

small adjustments throughout the mass. Among the adjustments, gliding on the cleavage planes of the calcite crystals is important, since such crystals are commonly very small and they provide a means of accommodation by innumerable, minute displacements without fracture.

The combination of superior strength, healing capacity, inflexibility, and adjustment by microscopic cleavage makes limestone the most competent among the sedimentary rocks in the zone of folding.

Sandstone is the symbol of rigidity,—and of weakness when broken. It possesses only moderate strength, about 0.8 that of limestone under confining pressure. It has no inherent cementing capacity. It offers no ease of accommodation by cleavage. It is thick-bedded as compared with shales, with which it is commonly associated, but is thin-bedded as compared with the great limestones. An individual sandstone stratum 100 feet thick is beyond the ordinary, whereas a limestone formation 1,000 feet thick is not uncommon. Sandstone lenses are often limited in extent and they grade out into interstratified layers of sandstone and shale, that is, into weak strata.

Because of its rigidity, sandstone in thick beds forms a strong strut, which transmits pressure, but if forced to bend it soon breaks or if held to the line of stress it shears irregularly. The broken segments retain their rigidity and in shales behave like a broken bone. Sandstone is therefore in the zone of fracture where shales and even limestone are in the zone of folding. Although locally very competent, it rarely affects the form of large structures, such as are controlled by massive limestones.

Shale varies in its relations to folding according to its constitution. Sandy shale is brittle, like sandstone. Argillaceous shale is tough and plastic. Calcareous shale is less plastic, but has the quality of recementing itself by the crystallization of calcite. None of the varieties has sufficient strength, however, to overcome the weakness caused by the flexibility which is due to the very thin bedding. It was observed by Heim that shales accommodate themselves to the folds assumed by more competent strata, or to the spaces within such folds; that is to say, they are incompetent, as a rule, to act for themselves or to control the action of other strata.

Shales nevertheless form very large and regular folds when

they occur in thick and extensive masses. Thus the Devonian of Pennsylvania, which is a large delta deposit of sandy shale and thin-bedded sandstone 8,000 to 10,000 feet thick, lies in very broad and simple folds, and, while the control was probably in the very massive, underlying limestone, the accommodation within the Devonian was facilitated by the somewhat uniform distribution of competency in the beds of shale and sandstone. Within the Devonian there was an approach to individual competency in each minor stratum.

With reference to relative competency to control folding we may class massive limestone formations as most competent to control large structures, sandstones as locally competent in minor folds, but liable to fracture, and shales as incompetent.

In any anticline in which different kinds of sedimentary rocks are involved, there are always stronger and weaker formations. The differences of strength may be very decided or relatively small. Where limestones, sandstones, and shales occur in thick deposits, they will commonly differ greatly in strength, and it is in such sequences that the typical structures of folded mountain ranges are developed. Often there is one formation, usually a thick limestone, which is *the* competent stratum of the series. Again, there may be a thick series of interbedded shale and limestone, or of shale and sandstone layers, which presents a certain uniformity of competency within its total thickness. A thick, argillaceous shale is the weakest, as a thick, massive limestone is the strongest of all stratified formations. These differences of competency materially affect the character of folds and of different parts of folds.

In the course of development of a competent anticline, the stronger formation tends to lift the overlying load. If it be fully competent, it will lift the whole load over its arch. If it be but partially competent, it will lift only part of the whole and must be assisted by adjacent strata if a competent structure is to develop. It may happen that a shale is not competent to raise and sustain even its own weight over the full span of the arch of a competent limestone. There are thus all degrees of competency, which depend not only on the nature of a particular formation, but also on the relative strength of the adjacent formations, as well as on the span of the anticline.

We may next consider the effect of competency on the manner

of folding within the competent arch and over it. The difference is marked if there be one formation which is notably more competent than the strata below and above it.

Since a competent anticline lifts the load, the section of strata within the competent arch must be relieved of load. And since there are all degrees of competency, the proportion of load lifted may vary from the whole to a small fraction. Whatever be the degree of competency, there must be *relief from load within a competent arch, under the competent stratum*. The effect in extreme cases may be to develop an open space. The underlying strata then come into the zone of fracture and are often broken, crumpled, and confusedly overthrust. A common result of partial relief is the well-known thickening of strata on the anticlinal axes (Figs. 19 and 31).

Above a competent formation in an anticline, the strata are subjected to an upward push from within. They are thus stretched over the arch. They may simultaneously continue to share in the compressive stress exerted in the direction of the stratification. The resultant stress may be one of more moderate compression or one of tension, according to the preponderance of one or the other of the opposed forces. The tensile stress will bear a relation to the relative competency of the lifting and lifted formations, being greater in proportion as the difference in competency is greater. The compressive stress will be weaker as the overlying strata are relatively less competent. Thus a weak shale, overlying a decidedly competent limestone, may be subjected to a definite extensive or spreading stress. Under sufficient superincumbent load, it may shear under vertical stress, suffer normal faulting, or squeeze out and become thin. An overlying sandstone may exhibit open, vertical fissures.

The effect of these relations on the forms of folds under a competent stratum and over it is very marked. Under it the effects of compression are intensified. Over it they are lessened or replaced by extension.

The competent stratum, rising from the underlying formation, transfers the load which it lifts from the axial region to the limbs of the folds. In them the strata are firmly held to parallelism, are often straight, and may be thinned by excessive pressure, while they thicken on the axes. The resulting fold in the competent stratum is of the type which is called *similar*, because the

limbs of the anticline make the same angle with one another in different strata. The axial regions are correspondingly thickened (Fig. 19).

Above the competent stratum, on the other hand, the lifted strata must conform to the up-arching mass. They will tend to be parallel to the upward convex curve and among themselves. The type of fold which is thus developed is characterized by the general parallelism of the strata throughout and is therefore called *concentric* (Fig. 18).

Similar and concentric folds have been distinguished in the descriptions of folds. It is obvious that they represent different mechanical effects and should be discussed as distinct effects, whether the discussion deals with the theory of folding or treats of its application to problems of an economic nature.

Turning now to the consideration of the transmission of pressure in strata undergoing folding, we recognize that the fact of folding having been initiated implies that the alternative phase of deformation by shear was more difficult and was therefore replaced by bending. In order that a pressure should bend a stratum it must have a component at right angles to the bedding. Under the assumption too commonly made, that the strata were flat and horizontal and the force was also horizontally directed, no such component could exist and no folding could take place. Evidently the stratum or the force or both must be inclined to the horizontal, so that the force impinges upon a bedding plane at some acute angle. When this is the fact, we have the simple case of a force acting against an inclined plane (Fig. 83) and the resolution of the principal force into two components, one at right angles to the plane and the other parallel to it.

Let us assume a sequence of strata already bent at some line and subjected to a pressure which coincides in direction with the bedding on one side of that line. Then the direction of initial pressure will be inclined to the bedding beyond the line of bending. The initial pressure will therefore be resolved into two components, each of them smaller than the original. Deflection of the strata, if it occur at all, will be caused by the perpendicular component, while the parallel component will be transmitted in the strata in the direction of the bedding beyond the bend.

If the strata are continuously curved, the resolution of forces

must occur at each element where the bedding changes direction. At each resolution the force transmitted in the direction of the bedding is reduced by an amount proportioned to the square of the deflecting component, until finally it is diminished to a relatively weak stress that is no longer capable of causing deformation. We thus reach the conclusion that no effective stress can be transmitted through an actively developing fold.

This conclusion does away with the necessity of assuming that any particular fold or a zone of folds must be buttressed on one side by an immovable mass, which opposes its immobility to the active pressure from the other side. In order that horizontal compression should cause folding, it is necessary, but sufficient, that there should be an initial bend or dip, adequate to develop an effective deflecting component. Such an initial dip may originate through downwarping or upwarping of the sediments, and it is demonstrable from the inequalities of thickness of sediments that deeply buried beds must have subsided so unequally as to be bent and warped initially. We are thus led to a conclusion which has an important bearing on the location and development of folded zones and mountain ranges.

Strata accumulating in a subsiding trough may be warped by unequal subsidence in such a manner that they acquire an initial dip or change of dip. This can hardly fail to occur where the deposits cover the zone between an area of subsidence and one of uplift. The more deeply they are buried, the greater the probability of warping and the more acute the probable change of dip. In deeply buried strata consolidation is advanced and the differences of competency are emphasized. Therefore, when such strata, so situated, are subjected to adequate horizontal pressure, they yield by competent folding. In the development of any fold, the force which is active in the competent stratum is exhausted in producing the uplift. Deformation of any area situated beyond the fold can occur simultaneously only through the action of a stress transmitted through rocks below the competent stratum, or subsequently when the competent fold is closed and transmits the pressure as a rigid mass.

This purely mechanical result explains why great depressions in the earth's surface, which become filled with sediments, the so-called geosynclines, are commonly raised in the form of folded mountain ranges. The question is not appropriate to this place,

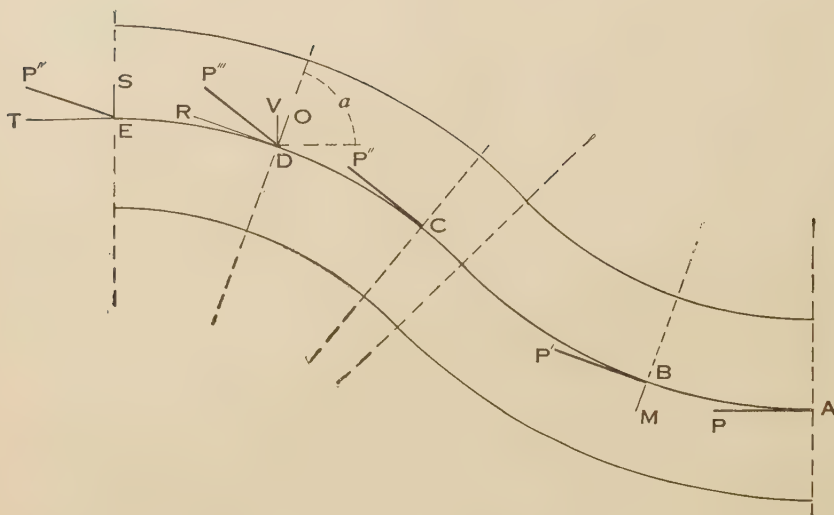


FIGURE 83.—Development of stresses in a competent fold:

Let it be assumed that an incompetent fold has developed to the curve *ABCDE* and that it is subject to a horizontal force *P*. Assume further that the surface *ABCDE* is a bedding plane and one on which movement may take place. Let the system of forces in all directions be in equilibrium, so that there is no motion and no work done, but let the resistance to shear be greater than that opposed to flexure, so that an increase in the value of *P* will cause the anticline to rise as a competent structure.

Under the assumption of equilibrium, the pressure *P* will be transmitted along the surface *ABCDE*, everywhere tangent to the curve and everywhere opposed by an equal resistance. If there is no movement there will be no loss, and *P* will everywhere along the surface *ABCDE* have the same value in the direction of the tangent. *P'* and *P''*, for instance, will be equal.

Let the assumed state of equilibrium be interrupted by an increase in the pressure *P*, in a gradual manner so that the rising pressure is the same throughout the length of the competent stratum. Then, as motion ensues on the surface *ABCDE*, the pressure *P* will be resolved into components perpendicular and parallel to *ABCDE*. Considering any two adjacent, minute elements of the curve as straight lines, the direction of pressure in the one nearer *A* is a tangent to the curve and diverges from the direction of pressure in the one toward *E*, by an angle equal to the angle between their respective radii.

In order to visualize the resolution of forces, assume that *C* and *D* are points immediately adjacent and may represent the minute elements referred to. Take *DP'''* equal to and parallel to *CP''*. Then the components *DO* and *DR* are active in the radial and tangential directions respectively.

The radial component *DO* owes its existence to the curvature of the bed, and depends for its value on this curvature. If the transmitted pressure remain the same *DO* increases if the curvature increases. In this case the curvature has been assumed to be uniform from *C* to *E*. Hence *DO* will not vary through this arc.

It would appear that the force DP'' would diminish at E to one equal to DR , but as there is no motion, DO is balanced and offset by the external resistances, which thereby deflect DP'' to EP^{IV} without loss.

If the direction of least resistance is vertically upward, the vertical sub-component DV of the radial component DO will be the effective force to produce motion, and this motion will first occur where it first becomes greater than the weight opposed to it.

Now the value of DV , expressed in terms of DO , is $DO \sin a$; a being the angle made by DO with the horizontal. If DO does not vary between C and E , that is, if the curvature is uniform, DV will be a maximum when the angle a is 90 degrees, that is, at the top of the arch. The lifting tendency will therefore become effective at the crest of the curve, at E .

Before any motion can occur, however, the competent stratum must be bent upward. This requires that a certain length of the stratum be raised, since the slab cannot bend unless its length in the direction of the arch be several times its thickness. The radial components along a portion of the curve, from E back to C for instance, must therefore grow strong enough to lift the load and to bend the competent stratum. This, under the assumed conditions, will result from a sufficient increase in the value of the original pressure P . When that pressure becomes adequate to develop the necessary radial components, the arch will rise as a competent anticline.

When uplifting begins, work is done and the radial components subtract from the successive pressures transmitted from element to element of the curve. The effect must be to diminish the transmitted pressure to a value at which it can no longer develop a competent radial component. Thus the distance to which the transmitted pressure may continue to be effective is limited.

The condition which determines the proportion of any radial component to the pressure transmitted to the corresponding point of the curve is the degree of curvature. The sharper the curve, the greater the radial component and the more rapid the exhaustion of the transmitted pressure. In the hypothetical case employed to develop the mathematical relations, the curvature was assumed to be uniform. In nature it would rarely be so, or if uniform while the anticline remained incompetent it would commonly become non-uniform as the competent structure rose under unequal resistances. Wherever the curvature originally was or later became sharper, the radial components would absorb a larger proportion of the transmitted pressure and, assuming the latter to be the same in adjacent sections, the arc of sharper curvature would rise faster.

The preceding holds true for those stages of development during which the dips are low. Those shown in Fig. 83 are much steeper than the initial dips in which competent folds probably begin to grow. In experimental work it has been found that a deflection of one degree, or even less, was sufficient to fix the position of a competent anticline. Competent folding probably begins, therefore, with very gentle dips, that is, in an attitude in which the radial component is but a very small part of the transmitted pressure.

It is evident that, just as the radial component has a vertical sub-component, so the tangential component has a horizontal sub-component. The latter lies in the competent stratum so long as the dips are low and exerts a shearing rather than a bending effect. But as the dips grow steeper, the bending effect increases in importance, with the result that the limbs of the fold are pressed together under the crest.

By an application of the principles deduced in the preceding paragraphs, the various types of folds: symmetrical or unsymmetrical, acutely arched or flat-topped, carinate or fan-shaped, may be explained as developments of competent structures.

but will be discussed more fully in that part of the work which deals with the current theories of deformation.

Analysis of Incompetent Folding.—Incompetent folding differs from competent folding in the direction of the deflecting stress and in the character of the resulting tension. As has been stated in the preceding section, competent folding is produced by pressure directed in the planes of the strata, when they are in a nearly horizontal position, and resolved into components parallel to and perpendicular to the beds as they bend. Since the angle which the pressure makes with the bedding is an acute angle, the

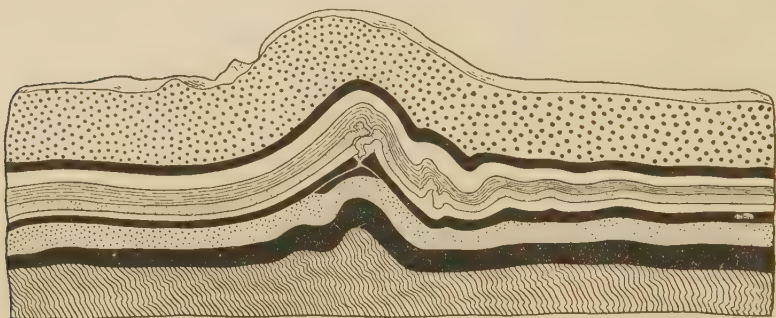


FIG. 84.—Section of model demonstrating the effect of competent folding. The model, composed of strata of wax and wax mixed with plaster, was compressed from right to left. The upper bed (dotted) was competent and lifted the load. Weak strata within the arch were thrust into the area of relief of pressure and there crumpled.

See "Mechanics of Appalachian Structure," *Thirteenth Annual Report*, Plate LXXVIII.

component parallel to the bedding is larger than that perpendicular to it. The folding mass, considered as a whole, is subject to tension in a vertical direction, as is demonstrated by the spreading in the axial planes of similar folds. Competent folding, therefore, is characterized by horizontal compression and vertical extension.

Incompetent folding is the result of a deflecting pressure which is initially directed at right angles to the strata, or nearly so, when they are in a horizontal or gently inclined position, and which also is resolved into components at right angles to and parallel to the stratification. But, since the angle which the direction of the stress makes with the bedding is a high angle, the perpendicular component is larger than the parallel component. Hence, it fol-

lows that the mass as a whole is subjected to vertical, or radial compression and to horizontal, or tangential tension.

Incompetent is a necessary preliminary to competent folding. The radial component cannot develop unless the strata have already been deflected from a flat plane and that deflection is incompetent flexure. Initial deflection occurs as a result of subsidence or uplift, or both, acting simultaneously on adjacent areas of buried strata. Horizontal compression may or may not affect strata so situated, theoretically, but it is a fact confirmed by general observation that it often has done so, and with sufficient power to cause competent folding, when sediments have accumulated to great thickness in a geosyncline.

The area of an incompetent flexure may be very extensive, as extensive as a continental plateau or an oceanic deep, or it may be long and relatively very narrow. In the same mechanical class we may place laccolithic domes, although they are genetically distinct. The essential fact in the development of an incompetent fold is that there has been subsidence in response to the attraction of gravity or there has been uplift due to one or another of several kinds of up-pushing. We may review the various conditions to which incompetent folding may be attributed, but without going into the theory of their origin in this analytical treatment.

Whatever the deep-seated causes may be, subsidence is a movement which affects very large areas of the earth's surface. Gravity is the evident and sufficient force. Subsiding areas are the gathering places of sediments, both continental and marine, and the earlier deposits, in course of subsidence and in consequence of subsidence, become deeply buried under the later ones. It is demonstrable that the earlier beds were practically flat when deposited, that the thicknesses of the overlying strata vary greatly over the area of deposition, and that the upper surface was also practically flat during and at the close of the process of accumulation.¹ There is, therefore, no escape from the conclusion that the older formations became flexed or warped during the progress of subsidence and in consequence of the vertical attraction of gravity. The structure thus developed is, by definition, an incompetent syncline. It is already well recognized as the "geosyncline" of Dana. It is not limited in occurrence to continental, marginal, or marine areas, and may be represented by the geosyncline of the

¹ WILLIS, BAILEY, "Mechanics of Appalachian Structure," plate LXIX.

Alps, by that of the Appalachians, by the basins of the Rocky Mountains, by the Valley of California, or by the Caribbean deep.

The converse of the geosyncline is the "geanticline," an upfold of similar dimensions. As an illustration we may cite the present elevation of the Appalachian Mountain region, a broad, low dome, 1,500 miles long and 600 miles wide. Exception might be taken to this example on the ground that it had never been covered with sediment and therefore could not be regarded as a flexure in strata, and strictly speaking the objection is valid; but the citation may stand to call attention to the very close relation which exists between incompetent flexures in strata and upwarps of deeply eroded areas, although in the latter the form can be traced only in a flexed peneplain.

The incompetent geanticline is better represented by an elevated plateau region covered with marine sediments, since in such a structure, as for instance in the Colorado Plateaus, the flexures and faults may be traced out in the strata. The very low dips, the very broad uplift cannot be attributed to horizontal compression applied to the strata themselves, but must be regarded as the effect of a general up-push affecting the entire area from below.

Turning to the consideration of smaller structures, we may class as incompetent anticlines the covering of batholiths and laccoliths. The strata in these relations have been bent upward by the intrusion of molten masses below them. The force exerted is radial upward and outward, at right angles to surrounding strata. The structure is, therefore, by definition, an incompetent anticline.

We have seen that in the development of a competent fold there is a distinction to be made between the activity of the competent stratum and the passivity of the incompetent beds. The latter are bent over the arch of the former by reason of the up-push of the competent anticline beneath them, and it follows that the upper or incompetent beds assume the character of an incompetent anticline. Competent and incompetent structures are thus associated in the growth of folds produced by horizontal compression.

Where the crystalline basement beneath a more or less heavy blanket of sediments is displaced, the strata must suffer a corresponding flexure of the incompetent type. The displacement of the foundation may be due to gravity and be subsidence of the

kind already discussed, or it may be in the nature of an upthrust. The latter is not uncommon in certain regions where a metamorphic sub-structure is under great compressive stress, as it is for example in the Coast Ranges of California. An upthrust fault, originating in the basement rocks and becoming active after a period of sedimentation, will lift the overlying strata on the edge of the upthrust block. The effect is to produce an unsymmetrical anticline, which, if it develops far enough, may pass into a normal fault. The strata, being stretched over the upthrust block, are in a state of tangential tension peculiarly characteristic of incompetent folds. Where anticlines occur in unconsolidated sediments overlying a crystalline basement, especially in regions where upthrusts are common, this type of incompetent fold may reasonably be inferred. The oil fields of the San Joaquin Valley exhibit illustrations, in which the Pliocene and Pleistocene formations are arched in long, narrow folds.

The mechanical effects of incompetent flexure are those peculiar to tangential tension, resultant normal faulting, and incidental crushing with minor compression features. Shales are fissured, loosened by horizontal extension, and thinned by normal faulting. Sandstones are jointed and the radial joints are opened. Limestones also are jointed, but the many minute fissures are not infrequently sealed by the deposition of calcite. Joints and normal faults tend to develop as strike joints and strike faults, with less pronounced jointing or faulting across the axis of uplift in domes or cigar-shaped folds.

Development of Folds.—In the prevailing loose use of the term folding, the development of both incompetent and competent folds is included. The similarities of form and the intimate association of the two types justifies the usage, even though they differ markedly in the mechanics of growth. But, in order that we may clearly understand their relations, it is desirable to trace out the development of the structures.

In its initial stage any fold must be of the incompetent type. Its deflection progresses with subsidence during the deposition of the strata in a geosyncline, resulting either in a broad, simple syncline or in synclines and anticlines in alternate pairs. The original distribution of these incompetent folds may be determined in any basin where the beds are exposed to view, by measurements of the variations of thickness. Observations are less numer-

ous than would be desirable for a generalization, but the evidence at hand indicates that, as a rule, the initial, incompetent flexures are convex upward as well as downward, as would be expected since irregularity of subsidence is more probable than regularity.

During the progress of subsidence, the forces which deflect the strata are essentially vertical. The downward movement is in response to gravity, and any up-arching is due to the lagging behind of that section as compared with adjacent sections. In order that competent folding should ensue a horizontal stress must become effective, and this may come about through any one or a combination of several conditions:

- (1) If the geosyncline be subject to horizontal stress from the surface down to an indefinite depth during the process of deposition, then competent anticlines will begin to develop from the incompetent arches when the curvature of the latter becomes sufficient to give the radial components adequate lifting power.
- (2) If the geosyncline be subject to horizontal stress only in deeper horizons during the progress of deposition, then competent anticlines will begin to develop only when strata which are adequately bent sink to that depth, or when strata which have sunk into the zone of compression become adequately bent.
- (3) If the subsidence of the geosyncline be not contemporaneous with the existence of a compressive, horizontal force, the structures of the geosyncline will continue to develop as incompetent flexures until such time as the sufficient force of compression may arise.

There is good reason to believe that all three of these cases have occurred in the course of the history of the various folded regions of the earth.

In the evolution of competent from incompetent folds, it is probable that anticlines first become competent, before synclines, since uplift must commonly be easier than forcible depression. Uplift requires that the radial component shall be adequate and that the rock shall be strong enough to lift the overlying load. The former is a function of curvature, a sufficient original stress

being assumed, and the latter depends upon the nature of the rock and the thickness of the strata. These points have been adequately covered in the preceding section.

The form of the competent fold will depend upon that of the incompetent flexure and upon the manner of application of the compressive stress. To illustrate we may consider certain cases.

Let it be assumed that the incompetent flexure is an arc of a circle, and also that the compressive stress is exerted equally from both sides. As we are dealing with earth forces, we will proceed most consistently by assuming further that the growth of the compression has been gradual enough to affect the entire length of the arc under consideration. Then, since the pressure in the direction of the bedding is uniform throughout and the curvature is everywhere the same, the radial components must be the same. Each radial component is resolved, however, into horizontal and vertical sub-components and the latter must do the work (Fig. 83). Being direct functions of the angles which the radial components make with the vertical, the effective vertical sub-components will increase in value toward the top of the arc. Any lifting effect will, therefore, be initiated in the top, or axial region of the fold. The stress which does the lifting is transmitted through the limbs and they consequently continue under compression. So long as the assumed uniform conditions exist the anticline will continue to develop as a symmetrical arch.

A different condition arises if it be assumed that the incompetent flexure is initially an uneven curve, that is, one which varies in its radius of curvature. It is obvious that the effective vertical sub-component will first become competent to lift the load at that point of the incompetent anticline where the sharper curvature gives the largest radial component and where the latter makes the least angle with the vertical. These conditions may not coincide in their maxima, but a resultant maximum will follow from their combination and competent deflection will take place first where that resultant becomes effective. There is in these conditions a definite tendency to exaggerate the initial inequalities of the curvature. Unsymmetrical competent anticlines result, therefore, from unsymmetrical incompetent ones.

The number of hypothetical illustrations might be extended by description, analysis, and experiment, but enough has been stated to show that the competent fold is a development of the

incompetent and that the form of the latter is commonly perpetuated, though exaggerated in the former.

It may also be repeated that the strata above the competent stratum in a competent anticline are lifted by the rising arch and therefore fold incompetently.

Dimensions of Folds.—The linear dimensions of folds include length, width, breadth, and height. In order that they may be defined and measured, it is necessary that the limits should lie in one and the same surface—a bedding plane, for instance.

The length of a fold is measured parallel with the axis or strike of the anticline or syncline and may be called the *strike length*. In common practice it is the distance on the chord of the arc formed by the rising and falling pitch of the fold, between the end points at which the arch or trough passes into another structure. As the latter are rarely well defined, the strike length is a somewhat indefinite dimension. In any fold the strike length may be compared with the length over the arc of the rising and falling pitch, and the latter, to distinguish it, may be called the *pitch length*.

The dimensions at right angles to the strike of the fold are the *width* and *dip length*. The width is the distance in a straight line from an axis of either kind (synclinal or anticlinal) to the adjacent axis of the same kind. The dip length is the distance between the same points measured over the arc of the stratum.

The *height* of any fold is the vertical distance from the crest of the anticline to the bottom of the syncline in the same bedding plane.

In speaking of the size of a fold, considered as a whole, we usually have in mind the two straight line dimensions, strike length and width. Too often, the condition that these can be measured correctly only between terminal points or axial lines is overlooked and a fold is called small simply because the exposed portion is small.

With reference to the size of incompetent folds, we may note that the strength or weakness of the strata does not enter into consideration as a limiting factor. For the beds are passive and bend like layers of felt over a mold. It is otherwise in the development of competent anticlines.

A competent anticline is a structure which lifts and carries weight. Its size must therefore bear a proportion to the strength

of the arch and the amount of the load. We may visualize the situation during development by recalling that the state of competency develops from a previous incompetent flexure, in consequence of the growth of the radial components of pressure. Other things being equal, the radial components develop with the curvature. We may thus conceive a strong stratum as beginning to lift the load on its arch when its curvature becomes great enough. As is explained in Fig. 83 the state of competency will be initiated at the crest, but it will spread from the crest down the limbs until the length of the span is such that the gently curved stratum can be bent to a higher arch by the radial components of the pressure sustained by the stratum. This length of span we may call the *inflexion length*, because beyond its ends the curve will be concave upward, and its ends thus correspond with the points of inflexion of the curve, at which it passes from the anticlinal to the synclinal portion of the structure.

The inflexion length of a competent anticline is thus the length of the arc which the radial components can deflect by increasing the curvature beyond that attained during the preceding, incompetent stage of development. The mechanical condition of the stratum is that of a horizontal column which is subject to a bending stress, and the resistance which the column offers under the circumstances depends upon the ratio of length to thickness. In engineering practice it is assumed that a straight column will not yield by bending unless its length is at least fifteen times its thickness. A less ratio would probably suffice for deflection in the case of a stratum already bent, but, on the other hand, a larger ratio might be demanded by the excessive rigidity imposed upon the rock by the confining pressures. We may get a suggestion from the proportions of the Nittanny anticline of the Appalachian folds of Pennsylvania, in which the competent stratum is a massive limestone, 6,000 feet thick, and the dip length varies from 35 to 48 miles.¹ If the inflexion length was approximately one-third to one-half the dip length, we may deduce ratios ranging from ten to twenty as corresponding to the proportion of the inflexion length to the thickness. However the actual ratio may vary from this approximation, the fact is clear that the inflexion length and con-

¹ WILLIS, BAILEY, "Mechanics of Appalachian Structure," Plate LVI and p. 267.

sequently the size of the competent fold increases with the thickness of the competent stratum.

Another factor beside thickness modifies the size of a competent arch, and that is the superincumbent load. We assume the thickness of the stratum to be fixed and therefore its inflexion length is also fixed. Now, when the arch begins to rise from off of the underlying incompetent strata, it is subjected to the shearing stresses set up by the load that it is lifting and its strength to resist these stresses is inversely as its span. The span on which the load might be lifted may correspond with the inflexion length or may be greater or less. The determining factor in regard to the length of the effective arch will be the inflexion length, if the movement is controlled by the weakness of the column to bending, or will be the load, if the maximum competent span be less than the inflexion length.

The inflexion length presumably increases, other things being equal, with the rise of the confining pressures as depth increases. But the competent span decreases with the added load of greater depths. Hence we must conclude that the size of competent folds is limited by the load when the competent stratum is deeply buried and that *competent folds diminish to moderate size at some not very great depth.*

The zone of "fracture and flow" or of folding is therefore limited in its downward extension, so far as folds of notable dimensions are concerned, and, while no very definite limit can be assigned for its base, it may be regarded as not extending below 30,000 feet, on the evidence of field and laboratory observations. Microscopic and sub-microscopic competent folds, of course, may form down to the limit of possibility of a microscopic open space, possibly down to 40 miles below the surface.

Analysis of Shear and Flow.—A shear in rock has been described as a clean cut. The illustrations drawn from specimens and reproduced in Figs. 35 and 88, serve to show how very smooth and flat the parting of a rock may be on a plane of shear.

It is also observed, as shown in Figs. 94 and 95, that a rock may exhibit a parallel, laminated, or fibrous structure, which it has assumed in the direction of one plane of shear, while it is cut cleanly across on the other.

It is the object of the following pages to state the mechanical principles underlying these structures.

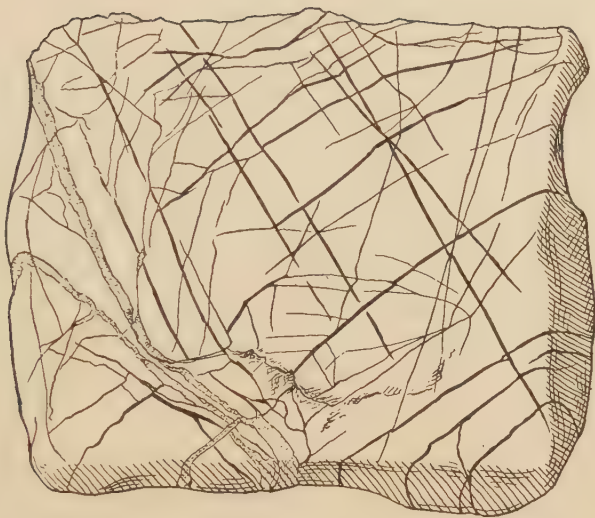


FIG. 85.—Description and Explanation. Figure 85 represents a piece of hard, brittle chert, which has been jointed by pressure. It is a type of deformation very commonly met with in the cherts of the intensely folded and faulted Franciscan formation of California.

The more continuous and better developed joints (shown by heavier lines) form two sets, which make an obtuse angle with one another. If the pressure that produced them bisected the obtuse angle, as may be inferred in accordance with the mechanical principles of shear, it was directed from right to left and from left to right. The rock of which the specimen was part was slightly shortened in that direction.

Minor joints cross the major ones at angles which vary between 35 and 48 degrees. They may be attributed to the action of a force acting at some later time from a different angle, either because the pressure had changed in direction or because the rockmass had been rotated. But that supposition, though not infrequently employed to explain relations of this nature, remains in most cases an unverified assumption. It is contradicted, moreover, in this case by the fact that there is scarcely any displacement on the major joint planes. It is difficult to conceive of conditions which would not cause faulting along them, if the force acted nearly parallel to one or the other set, as it must have to produce the minor joints as a subsequent and distinct group of fractures.

A different interpretation ascribes the minor joints to the action of the pressure which produced the major joints, but explains them as effects of components produced by the resolution of forces. The major joints being formed, the pressures upon them were resolved into components parallel and perpendicular to them. The parallel components produced no perceptible displacements, but the perpendicular components occasioned shearing stresses, in response to which the minor joints developed with very different degrees of perfection in different parts of the rock. It seems probable that this explanation has very wide application and should be considered as an alternative in many cases where otherwise there would be no recourse except to assume two distinct episodes of compression.

In mechanics a shear is defined as a parting or tendency to part under the action of two parallel, but opposed forces, which are not in line with one another. The action of the two blades of a pair of scissors is to produce a shear in the material cut. An iron plate is sheared when it is punched, the edges of the punch and die passing one another as the piece is sheared out. In these cases the shearing forces originate outside of the body that is sheared. A similar effect is produced when the overturned limb of a fold is crushed and drawn out between the upper and lower limbs, which move in opposite directions. It is sheared. (Figs 20 and 21.)

A column or a cube of rock may fail by shearing if a sufficient load be placed upon it, but in that case there are no external jaws or blades between which it is cut; the column or cube itself transmits the two opposed forces which tend to divide it. The two forces develop within the mass according to certain principles and are called *shearing stresses*.

We will now consider how rock shears under pressure.

If any solid cube be subject to pressure at one point, the pressure will be transmitted through the mass in every direction, radiating from the point. The rays of stress will diverge from the point in straight lines like rays of light and those which diverge at the same angle will form a cone, whose apex is at the point. There is an infinite number of such cones. The pressure exerted at the point is transmitted along each ray with some degree of intensity, but the intensity varies along different rays according to the angle which they make with the direction of the initial pressure.

Each ray of pressure is opposed by a resistance which is directly opposite and equal to it, so long as there is equilibrium. But if the initial pressure be increased to the amount which the strength of the material can no longer resist, the resistances will be overcome by the pressures forming that particular cone whose surface corresponds with the greatest difference between the rays of pressure and resistance. It can be shown mathematically that the theoretic angle which these rays make with the direction of the initial pressure is 45 degrees. In other words, the angle of the apex of the cone is 90 degrees. The surface of such a cone is known as the surface of *maximum shear*. (See Appendix B for mathematical demonstration.)

When rocks yield by shearing this ideal cone of shear is modi-

fied by (1) the distribution of pressure, (2) the law of least work, and (3) the special characters of the rock.

Pressure is not concentrated in a point. It is distributed over a surface and is exerted at all points of that surface. There are accordingly innumerable possible cones of shear, whose surfaces intersect in all directions at 45 degrees to the surface and at right angles to each other.

When the rock yields to these stresses by shearing, it does not part along all ideally possible surfaces. There is in any given case a certain number of surfaces, spaced a certain distance apart, on

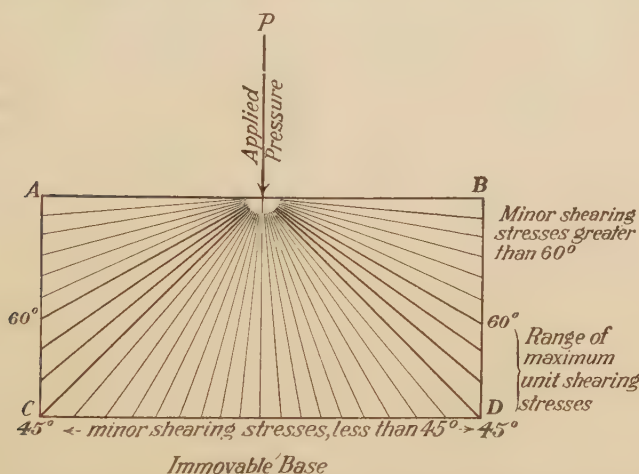


FIG. 86.—Diagram illustrating the range of position of possible planes of maximum shearing stresses in rocks, from 45 to 60 degrees in angle from the applied pressure.

which shearing demands the least expenditure of force. As a chain breaks at its weakest link, so the rock yields along these surfaces, which are distributed according to the law of least work at those intervals which require least effort. To part on more surfaces in a cubic foot would require more force, in proportion to the area of the shears, and to part on less is not possible because the resistance is overcome at that number of partings. Thus the shearing surfaces are spaced according to the force exerted per unit of surface and the resistance of the rock to shearing.

Furthermore, the law of least effort requires that the innumerable directions of shearing possible at one point shall be reduced,

by combination into that number which can do the work most easily. Since space has three dimensions, three is the least possible number of forces to which any greater number can be reduced, and it can be shown mathematically that those three forces will be so related to one another that each one will be at right angles to the plane of the other two.¹

The effect of this limitation of the effective forces to three is to substitute three-sided pyramids for the ideal cones of shear, and each pyramid is theoretically rectangular at the apex, that is it presents a corner of a rectangular cube or block, since the forces which define the planes lie at right angles to one another.

In each of the three directions in which the forces act, there will be a number of parallel planes of shear, spaced at those intervals which are determined by the intensity of the pressure and the strength of the resistance of the rock to shearing at right angles to each particular direction. Thus the effect of the initial pressure will be to divide the rock which is sheared into rectangular blocks. The blocks will be cubes if the resistances are equal in all directions, but will be oblongs if they are not.

The rectangular form of the blocks is again a mathematical deduction, which is modified by the physical character of the rock. The right angle is increased by an amount varying from 1 to 15 degrees by the tendency of the rock to spread sidewise under the pressure. The more rigid the rock and the more brittle it is, the nearer to 90 degrees will be the angle embraced between the planes of maximum shear. The more yielding the rock and the more it can be distorted without shearing through the mass, the larger will be the angle. Hence it follows that blocks cut out by the three systems of shearing planes are usually somewhat rhomboidal in form. Vice-versa, we infer that rhomboidal blocks, which are bounded by smooth planes, not due to bedding or in igneous rocks to shrinkage, are a product of pressure and shearing. (Figs. 34 and 87.)

The preceding statements regarding shearing may be summed up as follows: Any pressure, however slight, sets up in a solid mass certain maximum shearing stresses, which are definitely oriented. The stresses cause strain. If the strain be within the elastic limit there is no parting. If the strain exceeds the elastic

¹ HOSKINS, L. M. Flow and Fracture of Rocks as Related to Structure, in Principles of North American Pre-Cambrian Geology, by C. R. Van Hise, U. S. Geol. Surv., *Sixteenth Annual Report*, pp. 846 and 860, 1896.

limit, parting by shear ensues at certain intervals which determine the size of the blocks or rhomboids. The fact that there is parting as a result of forces acting parallel with the surface of separation implies that there must be some displacement of the sides. The amount of that displacement varies, however, from microscopic dimensions to miles and, as is yet to be explained, may be very slight on one set of shears while very great on the other.

Resistances play an important part in preventing or permitting the development of partings along planes of maximum shearing stresses.

We may assume a certain pressure to be exerted in any chosen direction upon a rock mass situated in the earth's crust. The resistances offered by the rock itself and by any other pressures acting upon it may vary in any manner whatever. But it will always be possible to resolve the system of forces into three, which are mutually perpendicular to one another and any two of which lie in a plane perpendicular to the third. It is convenient to postulate such an arrangement and to consider the greatest of the three forces as the pressure which produces shear, while the other two, lying in a plane perpendicular to the greatest, oppose unequal resistances to the development of shearing planes or partings. The direction parallel to, but opposed to, the weaker of the two resistances is the *direction of least resistance*, of which much account is taken in discussions of cleavage and similar structures.

The pressure at right angles to the plane of the resistances will produce in the mass below that plane maximum shearing stresses, oriented according to the nature of the material at 45 degrees or more from its direction. The stresses will lie in planes, arranged in conjugate pairs. Each pair will intersect in a straight line, the edge of a cube or rhomb, and any six intersecting shearing planes will define a cube or rhomb or parallelepipedon.

Since the resistances to shear are unequal, those conjugate shears which lie across the direction of least resistance will develop with a more perfect parting than those that are more effectively resisted. The mass will therefore exhibit partings along which it is distinctly, and it may be greatly, displaced, while in a transverse direction the partings are but slightly, or not at all, evident. We may call the former *active joints* and the latter *blind joints*. The occurrence of the two types is common and they are usually associated.

We may vary the preceding case by assuming that not only the greatest pressure but also the greater of the two resistances is to be considered as an active pressure, which may cause shearing. The line of least resistance will then be cut across by a system of shears, which originate with the latter, weaker pressure, and which will accordingly be more widely spaced. (Figs. 94 and 95.)

The development of secondary shearing stresses enters into the problems connected with faults in a manner which serves to explain the relations of the minor structures. Before taking up the analysis it is desirable to recall that any shear consists of a couple

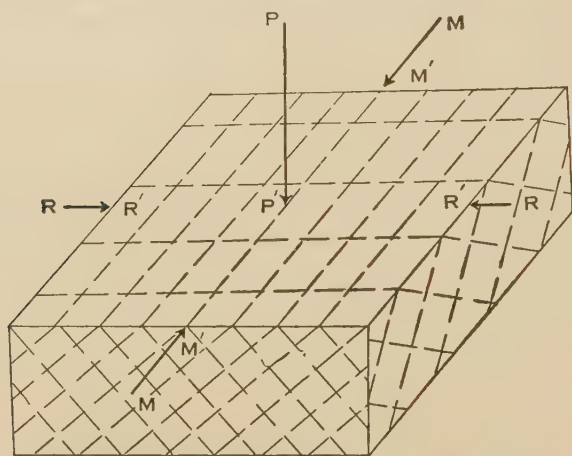


FIG. 87.—Diagram of three forces, mutually perpendicular, acting at all points of the mass; represented by PP' , the greatest, MM' , the medium, and RR' , the least force; together with hypothetical shearing planes produced by PP' .

of parallel forces acting in opposite directions, but not directly opposed. Both of these forces may combine simultaneously with a third, but the resultants form an angle with one another. If the shear has developed a parting, the two resultants are, furthermore, separated by it and lie in different segments. A shear cannot, therefore, be combined with another force, but either or both of its two forces may be.

We have also to bear in mind that a pressure which produces shearing is effective throughout the entire mass of the body acted on. We are apt to think of it as being applied only at the points or along the lines where shearing occurs, but that is not the case,

especially when it has been a long time accumulating. In geology we have to deal with conditions that change so gradually, as a rule, that stresses and resistances pervade great masses through and through.

Let it be assumed, then, that a parting has been developed by shearing along an active shear and that the pressure which produced the shear acts over the surface of the parting. Let the pressure in a particular case be vertical, due to gravitation, and the shear be inclined at 50 degrees from the vertical (Fig. 89). Assume that the pressure exerted at *A* by the weight of the mass above that point combines with the two forces of the shearing couple. It will augment the one in the upper segment and oppose the one in the lower segment. We may speak of the upper as active and of the lower as the passive segment, because of the diverse effects of these combinations.

If there be actual movement on the shearing plane, as on a fault, the pressure will be resolved into two components, in accordance with the principle of resolution of a force impinging on an inclined plane, and on either side of the fault there will result a component parallel with it and a component at right angles to it. Above the fault the parallel component tends to promote displacement. Below the fault the parallel component is neutralized by the opposed force of the shearing couple. The component at right angles to the fault and the resistance to it compress the rock in that direction. The effect is to set up planes of maximum shearing stresses, which may be sufficiently intense to cause actual shearing and parting. Movements in the lower, passive segment are opposed by the pressures acting on it and the development of distinct partings is difficult. In the upper, active segment, on the contrary, movement, though opposed on any shear that lies approximately horizontally, *AS*, is facilitated on those that point upward, *AS'*. The latter are, therefore, not infrequently evident in the hanging walls of faults (Fig. 89).

The deflection of the shear in the above case is in fact the development of a subordinate shear at an angle of approximately 330 degrees. The same principle applies in a different relation in a manner which explains the development of minor thrust faults. Let *AA* be a vertical fault plane, against which there is great horizontal pressure. Suppose that pressure to occasion shearing planes, of which the one pointing upward can become active. The

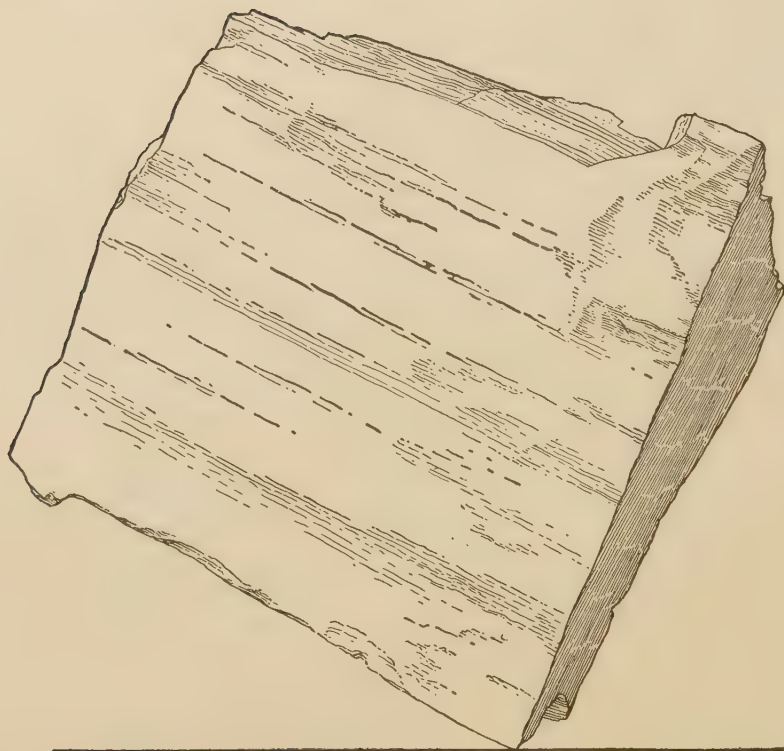


FIG. 88.—Description and Interpretation. The drawing represents a specimen of fibrous brucite from the Keystone magnesite quarry near Chewelah in the State of Washington. The mass of rock in the quarry is magnesite and dolomite from which it has been derived by hydrothermal alteration. The brucite is the product of intensive alteration on a vertical plane of transverse displacement. It forms a vertical sheet about eight feet thick and demonstrates the direction of displacement by striations, which run parallel with its fibrous structure. The specimen is oriented in the drawing in the position in which it stood in the quarry, with the fibers making an angle of 27 degrees with the horizontal. About 100 feet to the right of the specimen was the plane of a thrust fault of several thousand feet dip-slip, which had a dip of 70 degrees.

The diagram on the right of the drawing illustrates the relation of the thrust to the specimen and suggests a possible explanation of the stresses which



induced the development of the fibrous structure and of the remarkably smooth joint planes at an angle of 94 degrees to it.

It is assumed that a force PP' acted against the thrust plane and caused the dip-slip displacement. The exact angle of incidence of the pressure does not enter into the problem. PP' was resolved into the components $P'T$ and $P'C$. Of these the former caused the dip-slip, while the latter developed two planes of major shearing strains, each at 47 degrees to its direction. One of these shears was directed downward and met with such resistance that there was practically no displacement, although the rock parted by shearing. The other shear was directed upward toward the surface, which was within a few hundred feet, and met with less resistance than was opposed to motion in any other direction. It therefore became the plane in which shear, mass-movement, molecular movement, and recrystallization met with least resistance, and they developed accordingly.

Ordinarily, under purely mechanical conditions of stress, the planes of shear parallel to the direction of least resistance would be spaced at intervals and the rock would break out in blocks. But the hydrothermal action penetrated the entire mass and produced the general alteration and fibrous structure.

other may or may not appear. Acting on the active shear the horizontal pressure will be resolved into its components, and the perpendicular component may cause parting along secondary, or deflected shearing planes. The upper will be the more likely to become a parting and to suffer displacement. It is possible that the resolution of the horizontal force and the development of secondary shears may be repeated, and that a third active shear or fault plane may develop. If so, the attitude of the third fault,

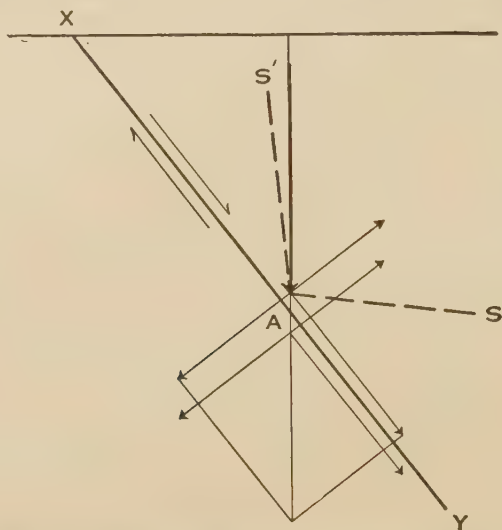


FIG. 89.—Diagram of pressure acting on a shearing plane XY at a point A , showing the resolution of the force into parallel and perpendicular components and the development of secondary shearing stresses AS and AS' in the active segment.

derived from a vertical primary fault, would be that of a low-angle overthrust. The San Andreas fault of California and some of its branches, including a small low-angle thrust that passes close to Stanford, appear to correspond to the structure described.

It will be noticed that in the analysis just discussed the secondary and tertiary faults develop progressively in advance of the main fault or shear. We may, accordingly, call this *progressive shearing*. It is sharply to be distinguished from *regressive shearing*, which is characteristic of Highland structure, as was shown by Caddell's experiments and is demonstrated by the relations of major and minor thrusts in all structures of that kind.

It is obvious from the preceding illustration that a pressure, sufficient to cause progressive shearing, may be so deflected as to cause shearing and displacement at angles departing greatly from its original alignment. One effect of this fact should be to make us careful in drawing inferences regarding the original direction of forces whose immediate results we may analyze. Another inter-

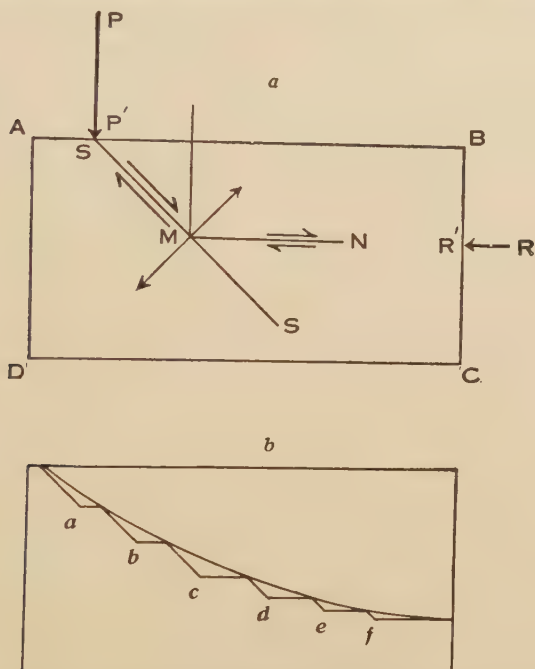


FIG. 90a.—Resolution of a shear at 45 degrees to the line of maximum pressure into the line of least resistance.

FIG. 90b.—A succession of shears resolved as in Fig. 90a, showing the curved line on which a mass will shear if shearing produces an appreciable amount of deformation.

esting application is to the explanation of the relations between pressure and schistosity. In this much-debated subject it has been contended on the one hand that the major pressure was perpendicular to the schistosity and on the other that the schistosity had developed parallel to the planes of maximum shear.

To apply the mechanical principle of the development of secondary or deflected shear to the problem, let us assume again that

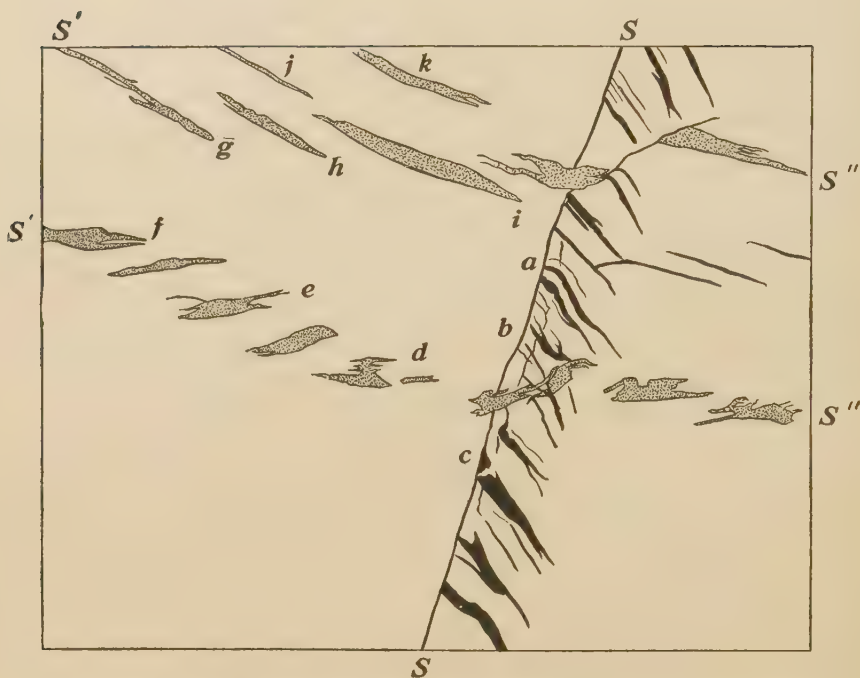
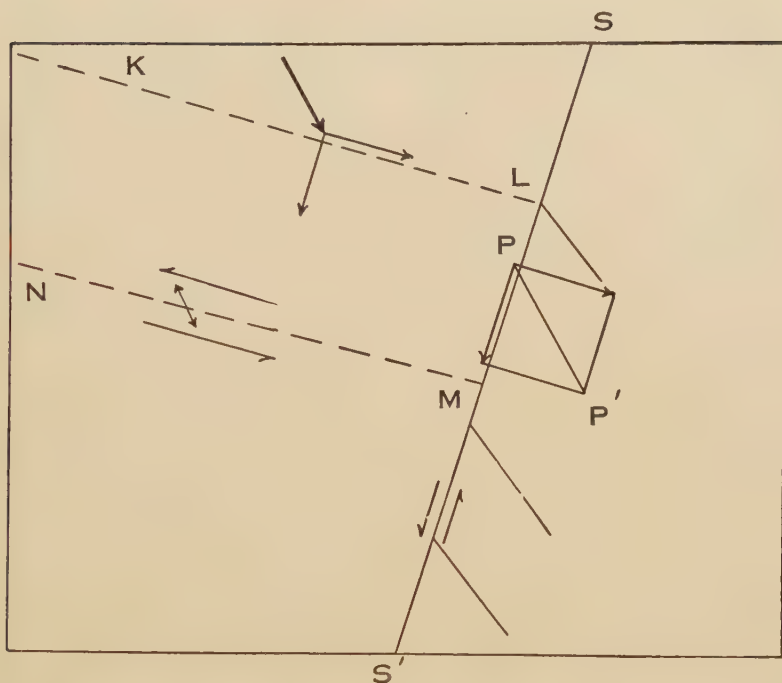


FIG. 91, *a* and *b*.—Description and Interpretation. The drawing represents a group of gash veins in quartzite, as they occur in a large block which lies on Huckleberry Mountain near Chewelah, Washington. The quartzite is gray and the filling of all the veins is white vein quartz, but the black and white have been used to facilitate the description. The area is about 3 by 4 feet. It is traversed by one major joint *SS*, to the right of which branch off numerous gash veins (black). Two other series of gash veins *KL* and *MN* (dotted) correspond in position with the lines of potential, conjugate joints, on which shearing has been imperfect. In the upper right-hand corner is a branching fissure, on which there appears to have been some displacement, but it is of small amount—not so much as would seem to be indicated by the dotted gash veins, each of which is interpreted as being due to a separate, local strain.

The diagram opposite shows the resolution of forces.

All of these veins may be attributed to a single, general pressure. Let *PP'* be the direction of that pressure which pervades the entire mass of the rock. Let *SS* be an active joint developed by it, while *KL* and *MN* are the lines of the conjugate shearing stresses on which the tendency to part is not realized. Let movement take place along *SS'* in the direction required



by the pressure PP' . Then PP' will be resolved into the two components parallel and perpendicular to SS' . The latter, if sufficiently intense, will produce two sets of shearing planes, approximately at 45 degrees to SS' , one of which will be kept closed by the tendency to movement from L toward M , whereas the other will be opened by that movement. The gaping of the resulting gash veins (black, a, b, c) is an indication of the amount of displacement.

The displacement from L toward M has the effect of revolving the joint-block from left to right along KL and from right to left along MN . The rotation promotes the tendency to shear on each line, but since there is no actual parting developed, the strain is distributed over a zone on either side of the joint-block. The upper zone comprises the gash veins g, h, i, i and k . The shearing resulting from the pressure PP' shortens this zone in the general direction from g to i , while spreading it at right angles to that direction. In the lower zone the veins d, e, f , etc., result from shortening in the direction ee' and elongation at right angles to it. These deductions are applications of the principle of the strain ellipsoid, and the student may do well to draw the appropriate shearing rhombs.

all the forces have been resolved into three, of which one is decidedly the greater and the other two not only less than it but unequal between themselves. Let us simplify the conditions still further by postulating that the intermediate force is neutralized by an equal resistance directly opposed to it. We shall then have only two forces to consider, the greatest and least, and the case will be practically that of a mass moving from a great unit pressure toward an area of least resistance. Furthermore, the two are at right angles to one another by assumption.

A section parallel to the plane of the force and resistance may be represented by the rectangle $ABCD$ (Fig. 90a), with PP' , the force, acting vertically downward and RR' , the resistance, acting horizontally. They will both cause shearing stresses, with approximately similar orientation, but those due to PP' will become active shears or planes of parting, rather than those caused by RR' . Assuming an active shear, SS' , we may resolve the pressure PP' on it and, because of the pressure perpendicular to SS' , we may develop a secondary shear, MN , which will be horizontal, if the angle of shear is 45 degrees in each case. Continuing the reasoning there develops a succession of shears a, b, c, d , etc. (Fig. 90b), each one of which may have a greater or less displacement. Supposing that the displacements on each one are very small, the broken line becomes a curve, such as is assumed by any substance forced to move under the postulated conditions of stresses. Cylinders of marble and granite, compressed by Adams in steel tubes which yielded at right angles to the applied pressure, sheared along curves of this form.

The amount of displacement on the shears in any particular direction depends upon the relative intensities of the pressure PP' and the resistance opposed to movement along that system of shears. In the case illustrated in Fig. 90b, the resistance to displacement along the shears at 45 degrees depends upon the firmness of the mass immediately beneath any point of pressure and may approach or equal the component of PP' , which would cause the slipping. Displacements in that direction would, therefore, be small. The resistance to displacement along the horizontal shears is exerted by RR' , which is by postulate relatively weak. These movements would, therefore, be large in comparison. It is desirable to bear in mind, in order that the concept of this shearing shall approach natural conditions, that the actual amount of



FIG. 92.—Description and Interpretation. The specimen of slate illustrated by the drawing presents systems of open gashes, which in several cases are separated by partitions that have been twisted aside like fibers of steel, as in the upper right-hand corner. Along the upper edge of the specimen runs the axis of a slight fold.

The facts of stretching and of flexure may be explained in accordance with the elongation and shortening of the axes of the strain ellipsoid during shearing, but the outlines of the specimen are artificial and do not represent the corresponding joints. The position of the latter may, however, be inferred.



FIG. 93.—Description. The specimen represented in this figure is a rod of green schist, which is long and rounded because the schistosity is fibrous and the transverse joints are spaced at long intervals. The form does not express the shearing rhomb, as that of the specimen shown in Fig. 95 does, but the process of development of the structure appears to have been very similar. The two rocks are alike in the relation of the transverse shears to the schistosity. They differ somewhat in the degree of development of the schistosity, which is greater in Fig. 93. The elongation in this case cannot be measured, but it may be estimated at several times the original length of the material by comparing the diameters of the fibers with their lengths.

displacement on any one shearing surface in schists may be microscopic or even molecular in dimensions and that the spacing of the shears is a function of the intensity of the pressure in contrast to the weakness of the rock. Great pressure acting on a yielding rock against slight resistance would result in close spacing and great displacements on the horizontal shears, that is to say, in thinly laminated, notably elongated schist.

The preceding appears to offer an explanation of the mechanical conditions bearing upon so-called rock flowage. When there is metamorphism, involving recrystallization, chemical activity is added to mechanical shear. We say advisedly *added*; for the rearrangement of matter in response to chemical, molecular, activity obeys the law of movement in the direction of least resistance and therefore must agree with the mechanical effects. Originating in a shearing at 45 degrees to the applied pressure, the structure is deflected to a position at 90 degrees to that pressure according to mechanical principles, which govern equally the megascopic, microscopic, and molecular rearrangements. It thus seems that the purely mechanical explanation of schistosity upheld by Becker may be brought into accord with that maintained by Van Hise on the basis of observational data.

In connection with the idea of rock flow it may be noted that the direction of movement in the solid rock is along shearing planes, which are oriented according to the definite laws of shear. Any pressure exerted by the solid against any adjacent body is directed by the shearing in an equally definite direction. Pressure cannot be exerted equally in any and every direction under these conditions, as it is by a liquid. It, therefore, seems improbable that hydrostatic pressures can exist in solid rock.

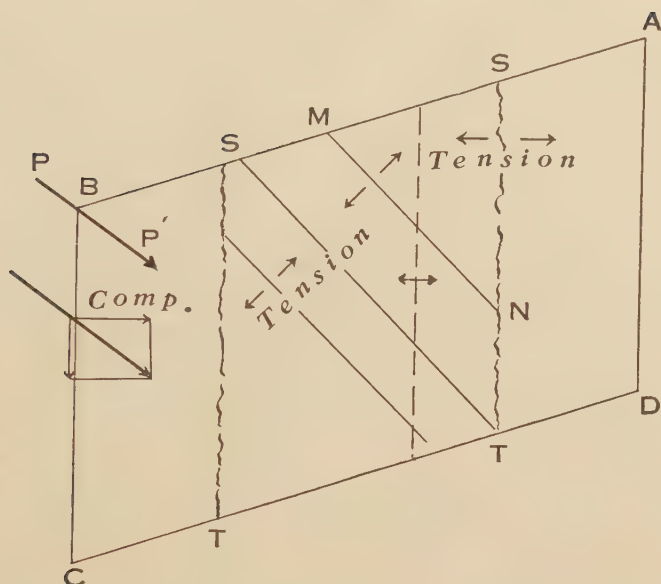


FIG. 94.—Description and Interpretation. The diatomaceous shale of the California Miocene is a thin-bedded formation, which is often intimately folded and cross-jointed. The drawing represents such a fold, an anticline about two-thirds natural size. Across the axis run two joint planes which form the face and back of the specimen. Diagonal to the axis, from left to right in the drawing, extends a series of lines, representing minute fractures. The outer strata are also broken parallel to the axis, as appears on top and on the left limb of the anticline. As seen from above, in plan, the specimen presents the form of a rhomb, shown in the diagram.

The facts may be interpreted as the effects of two distinct episodes of pressure or as the result of one only. In the former case it is assumed that the strata were folded until further yielding by bending would have involved distortion of the strata as a solid, cubical mass. Shearing then replaced folding as the easier mode of deformation.

According to the alternative possible explanation, the resultant of all the pressures upon the particular rock mass was a pressure PP' , directed as the bisectrix of the angle ABC (see diagram), the angle between the bedding planes and the joint planes. This is the lower, left-hand angle at the back of the specimen. The pressure resulted in two shears, one along the bedding planes BC , the other along the joints which form the faces of the specimen, BA and CD . Movement on the bedding planes occasioned the resolution of the pressure PP' , which must be regarded as general pressure, into the components parallel and perpendicular to those planes, with the result that the latter caused the folding.

The fractures ST on the crest and limb of the anticline are reasonably attrib-



utable to the stretching of the strata over the arch, with which they run parallel. The diagonal fractures MN , which are indicated only by lines along which one thin layer after another stops, are effects of stretching at right angles to their trend, that is, in the direction of the longer diagonal of the rhomb formed by the shearing stresses. They pertain, therefore, to the deformation by shearing. They could not have been formed after the anticlinal shape of the mass had been acquired, for they would then have penetrated more deeply. They thus seem to be evidence contrary to the hypothesis that the fold was first compressed and then sheared.

A consistent explanation of the facts may be suggested as follows: The pressure PP' was inclined to the bedding planes in their original attitude and caused folding as well as the development of shearing strains from the beginning of the deformation. In yielding to the shearing the rock at first stretched more in the direction of the longer diagonal of the shearing rhomb than it did perpendicular to the axis of the fold, but since folding and slipping of the beds was going on simultaneously the fractures due to stretching were confined to individual layers. As the folding became more pronounced the stretching parallel with the axis caused deeper and more evident fractures. Lines of stretching intermediate between the two major sets occur in the specimen and are shown in the drawing. They appear to represent a stage in which the stress was half way between its two ultimate positions, as it rotated from the earlier to the final direction of the tension.

This illustration should be compared with Fig. 95, which presents a similar set of conditions, differently developed.

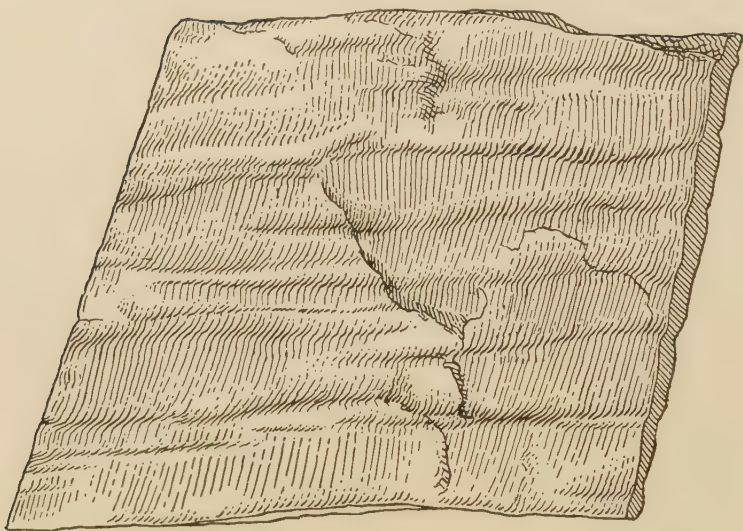


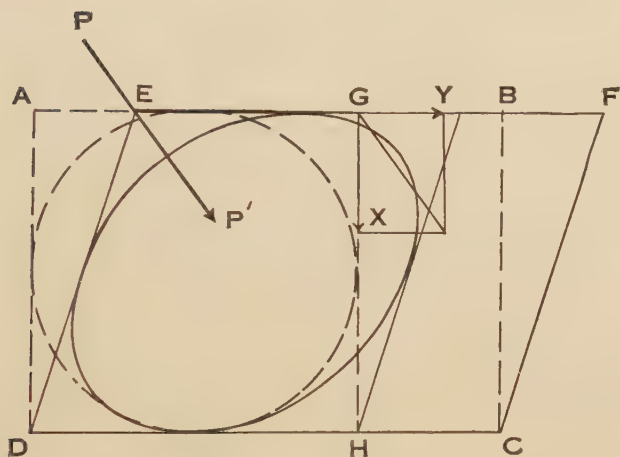
FIG. 95.—Description and Explanation. The drawing represents a specimen of foliated, green schist, a metamorphosed sedimentary shale, from near Chewelah in the State of Washington. Rocks of similar structure are of common occurrence in districts of moderate metamorphism. The original bedding of the shale was parallel to the plane of the paper. A readiness to cleave along closely spaced lines runs from left to right. Smooth joints, spaced at intervals of several inches, cross the other structure and define rhombs, as the drawing shows. Furthermore, the schist exhibits folding on a small scale, but commensurate with the thickness of the layers, with the axes of the folds running parallel with the closely spaced cleavages, that define one side of the rhomb.

The problem is to analyze the system of forces which may have produced these structures.

The rhomb is an effect of shearing stresses, which acted parallel to the two sides. Their development may be explained in two ways, by distinct assumptions that give the same result. The first is the assumption that the rectangle $ABCD$ has been transformed into the rhomb $EFCD$ by sliding of the material on planes parallel to AF and to CD , accompanied at the same time by shearing along the planes ED and FC . A circle drawn within any square, such as $AGHD$ is thus transformed into an ellipsoid which conforms to the rhomb $EKHD$. The deformation is therefore known as the development of the strain ellipsoid. The mechanical conditions appropriate to its development occur in bedded sediments, as, for instance, where rigid quartzites and shales are interstratified. The bedding planes are then parallel to AF and CD and, if AD represents the thickness of a stratum of shale, the quartzites above and below it may be assumed to have moved past it in the opposite directions from A to F and from C to D . This effect has been observed, especially in the quartzites of Baraboo, Wisconsin, and the interpretation has been extended to other cases as a general explanation of the action of forces in producing shearing and cleavage.¹

¹ LEITH, C. K. "Structural Geology," pp. 23, 24, 26, 31.

STEIDTMANN, E. The Secondary Structures of the Eastern Part of the Baraboo Quartzite Range, Wisconsin. *Jour. of Geol.*, vol. XVIII, pp. 259-270, 1910.



A variation of the preceding explanation follows from the assumption that the force which produced the shears bisected the obtuse angle between them, in the direction PP' . This force may be assumed, but simply as the resultant of all the forces and resistances acting in this plane. It will then suffice to have produced the observed shears, according to the postulate, but it must be regarded as a pressure affecting the entire mass of the rock, not as limited to the points at which the transverse shears, ED and FC , have developed. The latter are determined, as to their distance apart, by the law of least work. The pressure affects the entire rock.

Two effects remain to be considered: the development of the schistosity and of the folding. According to Van Hise the former should be due to a pressure acting in the direction GH , perpendicular to the cleavage, but under the assumptions made it is the effect of a diagonal force, PP' , as was argued by Becker. Following Van Hise, we would assume that the schistosity formed first, under normal pressure, and that the shears AD and FC , as well as the folding, were produced subsequently. The combination of effects is, however, capable of explanation as the result of the pressure PP' .

Let PP' be the resultant of all pressures and resistances. Let the resistance in the direction FE and CD be the least resistance. Assume that the forces act in the presence of conditions favorable to recrystallization of the rock as a schist. Then, when the shears ED and EF have been strained to the point of parting, movement will occur along EF . Because of that movement the force PP' will be resolved at any point G into components, GX and GY . GY , parallel to the least resistance, will aid in the flow of the recrystallizing minerals. GX , perpendicular to the least resistance, will be appropriately oriented normal to the schistosity and to the axes of folding.

CHAPTER VIII

FIELD METHODS

METHODS of geologic field work are individual. No two geologists work alike because geologic field work is thinking and no two men think alike. It is important to emphasize the thinking. Geologists enjoy their outdoor life, the freedom of the nomad, the delights of the artist, the inspiration of the poet, the aspiration of the seer, according to their gifts. But the geologist who would understand must think, think intensively, earnestly, and truthfully. His thinking is the soul of his work and his habit of thinking fixes his methods.

The practice of observing is very unequally developed, according to capacity and training. My friend hears ten birds singing where I hear none. I see the color, form, and texture of the stone he stumbles over. Not that I am deaf nor he blind, but our receiving sets are differently pitched. And as we differ in the kind of thing we observe, so do we differ also in the capacity to link our observations into a chain of thought.

Walcott, as it happened, was once out for trilobites in the quartzites of the Blue Ridge in Virginia. Many good fossil hunters had looked for them there in vain. We broke the ringing rock, where it is exposed in the gorge of the James River, for hours, but found nothing. The rock broke across the fossils, if there were any, and they were too thin to be seen. The next morning we looked across the Valley of Virginia to the Blue Ridge, 4 miles away, and could trace the low ridge formed by the quartzite along its face. Walcott called my attention to the ravine of a small stream, which crossed it, breaking the even ridge crest by a gap which lacked the sharp features of the river gorge. "The trilobites are waiting for us there," said Walcott. "They have been waiting a long time. Let's go." And there we found them in

abundance in the weathered rock shown by the gap, which split parallel to the bedding planes on which the trilobites had died.

It was not luck. It was method. The method of reasoning from the conditions of failure to those of success, the method which in its broader application consists in reasoning from correct observation to related inference; in testing inference by directed observation and passing to further inference; and so by alternate observation and inference arriving at a conclusion based on sound interpretation of facts.

That is the method of geologic thinking—a strenuous, exacting method, which requires the constant exercise of the best powers a man possesses, backed by sound training. Naturally, the ability to apply it grows with experience.

In offering the following outline of field methods, I would point out that they are individual, in that they are those which I find useful, and they are restricted in scope to the purposes of geologic field work in relation to structural geology.

Personal Qualifications.—The physical, mental, and moral qualities of a first-rate geologist must be of a high order, whether he follows the more scientific or the more practical branch of the profession. But taking these for granted, there is a distinction between two types of mind which determines what a particular investigator can do well. It is the distinction between the explorer of continents and the student of crystals, between the extensive and intensive application of thought. Many of the older geologists were explorers, not only in the sense that they travelled widely in little known lands, but also in that they reasoned widely on little known subjects. They were broad men, who grasped strongly the whole scope of earth science, and developed their speculations with corresponding daring. As our knowledge of earth processes and history has grown beyond the capacity of any one mind, the special student has increased in numbers and his individual labors are directed toward narrower fields. But the explorer and the specialist are both necessary to the progress of the science, and neither can do the other's work satisfactorily.

The broad class to which any would-be geologist belongs is usually apparent by the time he graduates from college; it is often indicated earlier in his career by the studies he prefers, by his grasp of the larger or more detailed aspects of his problems, and by the lifting power of his imagination. His studies should be

directed accordingly, either to ground him in the fundamental principles of geology and its allied sciences in general, while teaching thoroughness in key-studies, or to guide him step by step to that intimate understanding of the more limited range of fact and theory essential to success in the specialty in which he does well. Specialization, however, should be deferred as long as possible in a man's studies, in order that he may spread his roots widely. Otherwise, he is apt, like one of those Japanese cypresses whose roots have been stunted for centuries, to remain very small, even though he grows in years.

For the best understanding of structural geology, general ability should be accompanied by the capacity to see things in three dimensions, the ability to see through a solid body and recognize the form of its further side or the details of its internal structure. This is a qualification for mechanical engineering, but in geology the dimensions of the masses, whose positions in space and relations to one another must be grasped, are so great that the mind of a geo-mechanic is required. As in comparison with geologic eras the ages of human history shrink to seconds, so do the magnitudes of geologic structures dwarf human measures of length and mass. The uplift of the Himalayas from beneath the seas to the towering height of Everest is an effect which we can measure, it is true, but which is incomprehensible in our terms of inertia, force, and time. Yet the structural geologist should be able to understand the mechanics of that movement by application of principles which are worked out in the laboratory. To do so he must be able to see that mountain range in his mind's eye, to see through it, to see under it, and to realize how the forces are at work around it and in it.

Equipment.—Assuming that a man has the physical and intellectual equipment necessary to the practice of structural geology, his accessory instruments are very simple. Notebook and pencil, compass and hammer, are the two pairs of essentials. Other instruments are of service in special cases, but any that is not needed should be left behind because it wastes both time and attention.

One of the first problems of field work is to get the desired result without instruments. This requires that a man shall have developed the use of his own faculties in certain special applications to his purpose. He walks from one observation to another

and wishes to know the distance—he paces it. He ascends a hill and wishes to know its height—he steps it up by looking on a level with the eye and noting how many times the known height of the eye above the ground goes into the altitude of the hill. He wishes to draw an angle across the coordinates of the notebook page—he plots it by estimate, using the tangents of certain known angles and estimating between them. The methods of doing these things on the scale demanded by geologic surveying and within its permissible limits of error are detailed in subsequent paragraphs, but the purpose here is to call attention to the fact that they can be done without the bothersome tape, the misleading aneroid, or the unnecessary protractor.

Surveying for general geologic purposes should not be compared with that of the mining or civil engineer. Both the latter require great accuracy. But the geologist seeks to fix the dimensions and relations of masses of rock which have, as a rule, somewhat indefinite forms and outlines. He proposes to draw them on a relatively small scale. He is obliged to extrapolate beyond his measured data to a degree that makes the attainment of civil-engineering precision impossible. In general, therefore, it is true that proximate measures suffice, especially when they are checked against more accurate surveys or maps.

A geologist's notebook is something to be chosen according to his personal convenience, unless it be one of a series, in which case it should conform to the adopted style. The common surveying books are, as a rule, not well suited in form or in ruling. A preferred form is about 5 by 7 inches, with thirty to fifty pages of strong, stiff paper, surfaced to take and hold pencil well, ruled on one side only in squares of five to the inch, and bound between stiff boards. The ruling should appear on the right-hand page for writing notes or plotting surveys, while the left remains blank for sketches. It is a good plan to have the leaves punched to tear out and to file in a loose-leaf binder, so that the danger of loss may be minimized and different classes of notes may be filed in appropriate context.

The pencil should be as hard as HHHH, which makes a sufficiently readable mark, but retains its point and does not rub. It should be sharp and should be kept sharp.

The most convenient and adequate scale, both for ruling and measuring, is a strip torn off of one of the back pages of the note-

book and folded lengthwise parallel to the ruling. The fold in hard paper, creased on the flat surface of the notebook cover, is straight, and the ruling gives a scale that is identical with that of the page. The strip serves for temporary memoranda, the inside of it is a good place to sharpen the pencil, and if it blows away another can be had.

The pencil and scale may be conveniently carried in the notebook, under a rubber band, which is necessary anyway to keep the leaves from fluttering. With this equipment and arrangement no time is lost fishing in pockets.

The compasses most in use are the Brunton and the Gurley. The former is in more general use because it shuts up in a compact form, fits the pocket, and can be used for a greater variety of observations. The latter has the advantage of an open face, simplicity, and adaptability to the particular observations which a geologist most often makes. The essential elements of a good compass are a long, steady needle (not too wobbly), a distinct graduation, a clinometer, two levels, and a long straight side parallel with the north-south line. It is conveniently carried in a leather case on the front of the belt, where it may be slipped in and out readily and may serve as a rest for the arm in writing notes.

The hammer should be adapted to its purpose—chipping rocks for casual inspection, breaking out specimens, digging for fossils, trimming specimens—and should suit the convenience of its owner in weight, form, and length of handle. A first-class hammer which suits the taste, that is, expresses the character of its owner, can be obtained only by having it made to design. It should be of drill steel, tempered for rock, and deep enough through the head so that the handle will not work loose with prying. It is a good plan to wrap the handle with tiretape and wind it with cord for a grip. The handle should be a definite length for measuring; 18 inches with a hammer weighing $1\frac{1}{2}$ pounds is a good combination for all around work.

Accessory instruments, which are occasionally useful, are the hand level, the Abney level for slope measurements, the aneroid, and the traverse plane table. They are sometimes required because of the peculiar conditions of the work, but quite as often they are used because the observer is not trained to get results without them.

Note Taking.—The art of taking good notes, like the art of writing well, is difficult. The essential requirement is that the observed facts shall be stated adequately and without ambiguity. That which is adequate, I do not say full or complete, depends upon what is necessary to recall to the mind of the geologist all the facts of his observation which he would not otherwise remember when he comes to work up his notes. Facts come first. There are obvious facts, less obvious, and obscure facts. There are facts obviously important in relation to the immediate object of the survey and facts supposedly incidental thereto. There are facts understood and others which are not. Location, form, attitude, color, texture, kind, peculiarities, structure, classification, these and many more groups of facts may enter into the description of an outcrop, but as a rule we select that which seems at the moment significant and let the rest go unrecorded, if not unobserved.

It is therefore very advantageous to have in advance a clear idea of the class of facts of which the record is essential to the object of the survey. In structural studies the relative positions of strata or of other rock masses are the most important facts. The position of an outcrop is a primary fact, which we fix by tying it in to a line of survey that connects all similar observations. The bedding or other structural characteristic is noted next. The strike and dip, by which we may extend the beds along the surface or beneath it, are measured. Next we examine the rock for those peculiarities by which we may identify it with other occurrences or distinguish it from them, and having ascertained its relations, we are prepared to compare its position and attitude with that of other parts of the larger structure to which it belongs.

Let me suppose that an archaeologist is investigating the construction of an ancient building, which is partly gone and partly buried. His notes would relate to measurements of the exposed parts and would consist chiefly of sketches upon which he would record the details. In his mind he would trace out the plan of the buried portions, and upon that foundation he would visualize the original, complete structure. His notes, however, would usually state only the bare facts of directions and dimensions, with such classification of material as would enable him to recognize the part of the structure described.

In looking over old notebooks, I find that I have been that archaeologist, but my notes would seem very meager to anyone else, altogether inadequate as compared with the articles worked up from them. They have sufficed me, however, as records of definitely observed facts and as reminders of the related facts, all of which took their places in the hypothetical reconstruction that grew in my mind as I worked. How much a man should record may be a matter of choice or may be determined by circumstances beyond control; but he may count on it that he will often wish he had put down more or had looked for evidence of which he did not think. In other words, the scope of note taking should be as broad as the scope of observation and inference, but it is always limited, by conditions of time, weather, and companionship, to a fraction of that which should be set down on the spot.

It is desirable that notes be written in printed italics, that is, in a script which is not the usual, illegible handwriting of the college graduate, but a small, distinct lettering. Distinctness is an advantage, even to the man who has to read his own notes, and it is essential if they are to be interpreted by another. A small, or even minute, habit of lettering is required on maps and diagrams. It is advantageous to carry it through all the different classes of notes.

Though written small, notes should be widely spaced, and each separate observation should be set off from others by wider spaces. There should never be any possibility of doubt as to the connection of related statements or the distinction of unrelated ones.

A common source of confusion is the failure to locate an observation. We are pacing a traverse survey over a mountain and are recording the kinds of rocks of which it consists and their relations to one another. We observe, locate, and describe an outcrop. Passing on, we mentally take note of a variety of facts and arrive at the next station of our survey with them in mind, but the immediate observation of the facts at that station usually precedes the recording. The two groups of facts, those observed *since the last observation* and those seen *at this point* are then easily confused in the record. The initials S.L.O. (Since last observation) and A.T.P. (At this point) serve conveniently to separate the items.

Enough has been suggested to demonstrate, perhaps, that taking notes for scientific record is an art, which requires and will repay planning, painstaking care, training, and practice.

There are several systems which have been elaborated on the basis of experience and are adapted to different classes of geologic surveying. The original articles should be consulted.¹

Purpose of Structural Field Work.—Although it has been implied in much that has gone before, the purpose of field work for studies in structural geology should, perhaps, be more clearly defined. *Structural field work is measuring the details of the architecture of the earth.*

Measurement must be preceded by recognition of the kinds of materials of which the structure is composed and of their general arrangement in any part of the great structure in which they are imbedded. But we tread unknown ground. We must carry the identification of the rocks and the delineation of their outlines in larger or smaller masses along with the measurement of the attitudes and dimensions. The purpose is to survey—to survey, not the surface, as the topographer does, but the internal arrangement of the strata, or of the igneous or metamorphic rocks, as determined from surface measurements.

The purpose becomes more definite when we are confronted by a specific case. For instance, the delimitation and measurement of the horizontal strata of the wall of the Grand Canyon of the Colorado demands simply vertical measurements of the thicknesses of the strata, but the purpose with which that work has been done has been to afford data for interpretation of the record of geographic changes corresponding to the changes from limestone to sandstone or to shale. The latest survey, by Noble, is an example of the care with which even so simple a type of architecture should be investigated.²

Or we would ascertain the distribution of anticlines and synclines in a region of open folds, like parts of Pennsylvania or the Jura mountains. We observe the strikes and dips of the strata, identifying as often as possible some selected key stratum, but it is essential that the relative horizontal and vertical positions of the observations should be determined and, to that end, a map must be

¹ WILLIS, BAILEY, Graphic Field Notes for Areal Geology, *Bull. Geol. Soc. Am.*, vol. 2, pp. 177-178, 1891. CAMPBELL, M. R., Rapid Section Work in Horizontal Rocks, *Trans. Am. Inst. Min. Eng.*, Colorado Meeting 1896. KEMP, J. F., Geologic Bookkeeping, *Bull. Geol. Soc. Am.*, vol. 16, pp. 411-418, 1905.

² NOBLE, L. F., A Section of the Paleozoic Formations of the Grand Canyon at the Bass Trail, U. S. Geol. Surv., *Prof. Paper* 131-B, 1922.

available or must be made. The investigation of the rocks is thus accompanied by observations for position. Similar requirements are set where the relations of the more irregular, complex rock-masses are involved, as in the study of intimately folded and faulted sedimentary, igneous, and metamorphic rocks. The classic work of Albrecht Heim,¹ that of Peach and Horne,² and that of Pumpeelly, Wolff, and Dale³ afford illustrations of the skill with which such investigations should be executed.

Or the investigator may face the task of unraveling the relations of the pre-Cambrian complex, in which the original character of the rocks and their original relations are obscured by subsequent alterations to the extent that the solution defies any but the most patient and penetrating research. The great work of Van Hise and his associates in the iron ore regions of Lake Superior stands as one of the most intensive and fruitful investigations in this, the most difficult, branch of structural geology.⁴

It is not within the scope of any single manual to go into the details of the various methods which different observers have used in pursuing the investigation of more or less complex structural districts. In fact no geologist, however experienced, can foresee anything more than the general scheme of his method of attack, until he has entered the field. From the beginning, his ingenuity should be exerted to discover the critical aspects of his problem and to develop a method which will lead most directly to an understanding of its significant facts. The more he knows about surveying, mechanics, chemistry, physics, geology in its several branches, and Nature, the readier will be his invention of method and the more penetrating his insight into the secrets of the mountains.

Nevertheless, experience eventually formulates a certain general method of attack on a structural problem and, although it will always remain an individual method, mine may be helpful to others

¹ HEIM, ALBRECHT, "Mechanismus der Gebirgsbildung," 1878.

² PEACH, B. N., and HORNE, JOHN, Memoir on the Geology of the North-west Highlands of Scotland, Geol. Survey of Great Britain, 1907.

³ PUMPELLY, R., WOLFF, J. E., and DALE, T. N., Geology of the Green Mountains, Mass. U. S. Geol. Surv. *Mon.*, XXIII, 1894.

⁴ VAN HISE, C. R., "Principles of Pre-Cambrian Geology." VAN HISE, C. R., and BAYLEY, W. S., The Marquette Iron-bearing District. U. S. Geol. Surv. *Mon.*, XXVIII, 1897, and other monographs of the same series by Van Hise in co-operation with Leith, Bayley and Clements.

as a suggestion for the development of their own. My experience has led me to something of the following scheme of investigation to ascertain the general structure of a region, which, although the procedure is not necessarily systematic, had best be presented under successive headings.

Physiographic Questions.—Physiography, as I understand it, is the expression of the interaction of the earth-forces with those of the atmosphere, and the physiographic ensemble or landscape of any region is the record of that geologic period during which they have worked together; that is, it is the record of the history of the region since it last became a land area. Many lands retain features which go back to the Cretaceous age. Practically all the mountain elevations of the world are younger than Cretaceous. Hence the physiographic record contains the story of their uplift.

Among physiographic features, streams comprise the oldest survivors, or surviving remnants, and also the youngest developments in response to earth movements. They thus embody the longest record of the history of the land. This is not a treatise on stream development and conquest, but certain lines of analysis which bear on structural studies are appropriate.

With reference to the structure of any district, streams fall into three classes: (1) Those which flow in courses bearing no definite relation to the strike of the rock masses. (2) Those flowing parallel to the strike. (3) Those flowing at right angles to the strike.

The first are interpreted as having become superimposed upon bedrock, on which they did not originally grow, or as being older than the mountain uplifts across which they now pursue eccentric courses, or as having been directed in peculiar channels by glaciers or by volcanic lava flows. The conspicuous examples are great rivers, like the Colorado, the Ohio, and the Columbia. Their history is complex and is significant in structural investigations only in relation to broad geographic problems, except where some detail is adjusted to local conditions.

Rivers which flow parallel to the strike of the rocks, or to the general trend of the ranges or ridges, are adjusted to the outcrops of the softer strata or to lines of crushed rock along a fault plane, and they trace out the plan of the structure in so far as it is expressed in the arrangement of the weaker rocks.

Streams that cross the structure at right angles have usually grown upon a slope, parallel with its line of most rapid descent.

They took the shortest course to the lowland or to the sea. They had the steepest fall. They were accordingly the stronger and, invading the territory of longitudinal streams, they have captured them, providing they are old enough.

Streams are extremely long lived and very tenacious of life. Those of an older generation often continue to exist in sections as parts of a younger system, by which they have been captured and dismembered. The directions of flow and the angles in the course thus register older and younger controls, which were inherent in the structure of the rocks or due to disturbing earth movements. The stream pattern, therefore, has a direct relation to the facts of structure, as they exist, and to the successive episodes of tilting, folding, and faulting by which the attitude of the surface has been modified. The examination of the pattern, whether on a map or on the ground, is accordingly one of the most immediate approaches to an understanding of the structure.

The principles which govern the growth of streams and the manifold conditions that determine their adoption of a course, as individuals or in systems, should be known to the structural geologist.

The interpretation of structure according to physiographic evidence may also be based on the warped, tilted, or displaced positions imposed upon ancient topographic surfaces, whether they be mature landscapes or peneplains. In this light an old topographic surface is often as significant as a fossiliferous limestone or other well-defined stratum.

It is assumed that the surface is so developed and so distinct from younger surfaces that it can be recognized and identified in whatever position it may survive. Thus many physiographers have seen the Cretaceous peneplain in the even crests of the Appalachian ridges and, to take a very different case, the Pliocene valleys of the Coast Range of California are obviously distinct from those of later development. Each one in its own province affords a means of determining the amount and character of the displacements it has suffered.

On entering a district for structural studies it is desirable to determine whether the youngest structures are alive or dead. In the case of earthquake regions there is no doubt, but even where there is no direct evidence of life the mountain uplifts may be active in the sense that a slumbering volcano is active. Even

though the movements be so slow that the idea of catastrophe is excluded, as is generally the case, the movements may be in progress and faulting or folding may be developing. The evidence is then to be sought in the relation of the oldest topographic surface to the underground structure. Does it cut undisturbed across the folded or faulted strata or has it also been warped, folded, or faulted?

In regard to the distribution of structures that are dead and those that are not one may venture a generalization. Countries bordering the North Atlantic, from Florida round through the United States, Canada, Greenland and Great Britain to Germany, are structurally dead; that is to say, the folds and faults which affect the rock masses in those regions were formed and the forces which produced them had ceased to act through that particular mechanism before the Cretaceous peneplain, the oldest topographic surface there known, had been produced by erosion. Subsequent movements of the earth's surface have taken the form of broad upwarps. Remnants of the Cretaceous plain may be detected in the Atlantic provinces and there are many erosion features of Tertiary date, but there is no local ridge or valley which owes its existence to concurrent deformation. The relief is solely an effect of resistance of the harder rocks to erosion.

In contrast, the Pacific borders are structurally alive. From Cape Horn via Alaska and Japan to the East Indies the coastal ranges are in active movement. Upthrust faulting is the dominant mechanical effect. Some thrusts, like the San Andreas fault, are at present very much alive. Others are dead. The living are distinguished from the dead by their relation to the Pliocene topographic surface, which is displaced by the former, but which extends without offset across the latter. In California and no doubt in other mountainous lands, there are certain large mountain masses, of very complex internal structure, surrounded by live faults. Over their summits, at a high elevation, stretches the gently modulated Pliocene landscape, eroded across folds and faults of the first magnitude. They are evidently older than it and have been inactive during the period of its completion and elevation to its present position. But the Pliocene surface is cut by the marginal faults and is displaced along them. Sometimes it has simply lagged behind as the surface of another, less elevated block, sometimes it has been depressed by the downward rotation

of the mass that underlies a valley. Sometimes it is not faulted, but is bent down in a convex mountain slope and passes beneath the valley as a syncline. It then is a folded erosion surface.

The geologist who possesses an eye trained for physiography can read the active structure of a live country as he scans the landscape. Most students, however, are taught in the dead lands and the appearance of a live mountain or thrust fault is unfamiliar.

Another clue to the structure of a district is to be found in the distribution of hard and soft strata and other rock masses, as brought out by erosion. It is a very old and well-known clue, but is not always employed with the penetration that makes it most useful. It rests upon the principle that a resistant rock is represented by a ridge or hill and a yielding one by a valley, provided that the surface has been modeled by erosion. The form of the ridge, and sometimes of the valley, more or less definitely expresses the attitude of the strata, exhibiting dip slopes or jointed

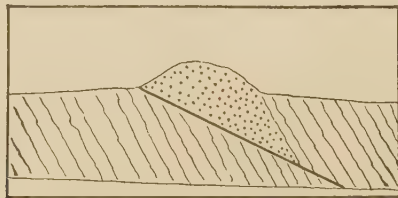


FIG. 96.—Overthrust postulated on evidence of a valley crossing a quartzite ridge without change in the grade of the valley floor.

faces, and thus indicates not only the extension of the stratum, but also its position in reference to the structural axes of the area. The discontinuity or abrupt ending of a well-defined feature is especially significant, and this applies to the vertical dimension as well as to the longitudinal.

Thus, for example: A deep valley crossing the strike of a monotonous mass of slates retained an even floor where it cut through a high ridge of quartzite. From the road in the valley the quartzite could be seen to be dipping about 60 degrees, but it did not cause any cascade in the stream nor appear in the road banks. Therein was the evidence of a fault—a fault of some kind because the quartzite was cut off before it reached the valley floor; probably a thrust because the angle of dip of the fault must be considerably less than 60 degrees to cut across the thick bed before

it could get down, in part at least, to the valley floor. The alternative of a vertical fault was entertained, but not for long after examining the crushed and slickened rock of the lower part of the quartzite. Thus the type of structure and the position of what afterward proved to be an important thrust were fixed in driving into an unknown, forested mountain district. (Fig. 96.)

The use of physiography as a key to the interpretation of structure thus falls into three categories: the study of stream patterns, the identification of old topographic surfaces in inconsistent positions, and the explanation of the distribution of hard and soft rock masses as brought out by erosion. Given good maps and the method can be applied in a preliminary way by inspecting them. Its efficiency is directly proportioned to the geologist's understanding of the principles and processes involved in the development of landscapes or of the details of streams, hills, and valleys. Both efficiency and confidence grow with practice and extensive observation.

Methods of Surveying.—While physiography may be employed to very great advantage as a means of interpretation of the structural features of any view, it does not afford measures of form or dimension. For that purpose surveys must be made. There is also the necessity for intimate observation of the kind, attitude, and mechanical condition of the rocks, which demands that the geologist shall get close to them. This involves going from point to point, usually on foot and the more on foot the better.

Surveys for topographic or mine maps must be executed with the plane table and alidade, transit and stadia, or other instruments which give results that are up to civil engineering accuracy. The geologist is fortunate when such maps have been made. If not, he should know how to make them if necessary, but topographic surveying cannot advantageously be combined with geologic surveying. The two operations should be carried out separately, whenever possible. They are incompatible, the former being precise, instrumental measurement, the latter consisting of observation and interpretation of natural phenomena. Both demand close attention and neither can be performed properly with divided attention.

For this reason instrumental work should be reduced to the minimum in geologic surveying. Methods of approximation should be used wherever they lessen the demand on attention

for determining accessory facts, and methods of checking approximate results should take the place of too constant application of the mind to securing more precise measures.

For measuring distances, whether traversing roads, mountain trails, or pathless slopes, the wheel or the pace is the unit most readily available. The former is limited, of course, to passable routes, generally roads, although an adaptation of the wheelbarrow can be used on paths. The pace has no limitations as to its availability in time or space.

Pacing is stepping off a distance, and as it is usually conceived is a burdensome process. Pacing when practiced until it becomes a habit is simply walking with a subconscious knowledge of the number of steps taken and does not materially distract from other observations. In order to reduce pacing to walking one must take one's natural step. In order to reduce counting to a subconscious rhythm, it should come at not too frequent, but fixed, intervals. These objects are accomplished by walking as usual and counting every fourth step. My pace is thus $11\frac{1}{3}$ feet, numbering 460 to the mile, or 290 to the kilometer. Another's may be 10 feet or 12. It does not matter what it is, provided it is the sum of four convenient, customary steps.

Starting out with the left foot, the count runs naught, naught, naught, one, and ends on the right foot. When the count of ten is reached, the pacer, instead of saying the third naught, says one, thus: naught, naught, one naught. Similarly, twenty-five would be naught, naught, two, five. When a hundred is reached, the hundred digit takes the place of the second naught. Thousands are counted on the first step. It will be found then, that units fall on the right foot, tens on the left, hundreds on the right and thousands on the left. This distribution is a help to the habit of automatically registering the hundreds and tens, which are easily skipped when counting every step.

Walking on roads or trails, or across grassy plains, there is no difficulty in keeping a natural step of average length, but up or down hill, rough ground, boulders in a stream bed, underbrush and windfall, or snow, require adjustments.

Ascending or descending a slope which invites one to lengthen one's step, it is better to shorten it intentionally and to count six steps instead of four to the pace. When the slope is one on which

you turn the feet out to get a better grip, eight steps to the pace may be counted. In any case the pace remains unchanged in length. Similarly, six or eight steps may be counted to the pace to reduce the length of a winding path to the length of the straight sight across the bends. This requires practice in estimating the ratios of diagonal lines to the side, but it pays in the saving of many short sights.

When the obstacles to ordinary walking are such that paces cannot be stepped off directly, in climbing through underbrush or jumping from stone to stone, etc., recourse may be had to eye-estimate of paces. This requires attention. One casts the glance ahead at each pace to a stick or stone which lies a pace (four ordinary steps) in advance, and counts the pace on passing it. The method enables one to carry a fairly close estimate of the distance traversed over ground that defies any other means except stadia or triangulation, and in forests where a line would have to be cut out for them.

Pacing, like typewriting, is a question of much practice and requires attention until the subconscious reaction of the mind to the swing of walking is established; but it can be practiced in the daily happening of going somewhere. Once acquired, the habit is not easily lost and constitutes a valuable asset for the geologist, since it is always instantly available, anywhere. Artificial aids, such as counters, should be avoided. Their use implies a weakness, which should be overcome by exercise.

Time-traversing is a method of observing distances which is much used in general exploration and may advantageously be employed where pacing is out of the question. It is based on the estimate of the rate of progress between each two points at which the observer pauses and upon notations of the exact times of departure and arrival. The elapsed interval multiplied by the rate of progress per minute or per second gives the distance. A somewhat steady rate of advance over somewhat long stretches is desirable in using this method. It has been employed by Russian explorers, and the maps of Mongolia are to a very considerable extent drawn up from route maps made by them in this manner while riding horses or camels. Dr. Hamilton Rice has employed it in extensive surveys of the Amazon and Orinoco basins by launch and has recently called my attention to a device, consisting of two scales drawn on two sides of a right angle triangle, which does away with

the necessity of multiplying. On a horizontal scale lay off distances; on a vertical scale lay off times in minutes and seconds; draw an hypotenuse to correspond to the rate of travel, or to various rates. Then the distance corresponding to any time elapsed may be read off by following the horizontal across to the hypotenuse and noting the distance on the scale at the top.

Time surveys have for the geologist the disadvantage that the psychology of the method is opposed to his purpose of detailed observation. Seconds become altogether too numerous when noted as such, yet if an observer hesitates thoughtfully over an outlier they may be of great value.

Compass-sighting and revolver-shooting are comparable actions, with which the ranging of the transit or heavy gun is in strong contrast. A compass mounted on a tripod is as much out of place as a revolver on a gun carriage. In each case the freedom of handling for which the implement was designed is sacrificed.

The geologist's compass may be held in the hand, at a convenient focal distance from the eyes, about the level of the belt, and be directed on the desired course without looking through the sights. The ability to do this within the limit of error permissible in geologic traversing is readily acquired by practicing ranging of near and distant objects in a straight line. The graduation of the compass should be one that can be read at the distance at which the compass is customarily held. The needle is best read by halving the swing while it is in motion, but may be allowed to come to rest if that is found necessary in order to be sure of getting the sight in the right line. The permissible error in good traversing is plus or minus 1 degree, or 20 feet at a distance of 500, provided that the scale on which the sight is to be plotted is not larger than 1,000 feet to the inch, 1 : 12,000.

In plotting the observed course on the field sheet there are three operations: laying off the angle, drawing the line, and scaling off the distance. The manipulations are reduced to their simplest terms by abandoning the protractor and using as a ruler and scale a strip of paper torn out of the notebook and folded so as to give a straight edge.

The protractor can be dispensed with, provided one knows a few ratios of coordinates, corresponding to the natural tangents of certain angles. Thus:

1 : 10.....	6 degrees	1 : 2.....	27 degrees
1 : 6.....	10 degrees	4 : 7.....	30 degrees
1 : 4.....	15 degrees	2 : 3.....	34 degrees
1 : 3.....	18 degrees	5 : 6.....	40 degrees
4 : 10.....	22 degrees	1 : 1.....	45 degrees

These may be laid off across the reticulated page either from the horizontal or vertical, and may be used for any one of the angles enumerated or for its complement. If the observed angle is not one of those whose ratio is given, the actual angle can be plotted by estimate between the positions of those on either side of it.

The methods of sighting courses with the free compass and of plotting them by coordinates are methods of approximation and are subject to the limitations imposed by conditions of adequate accuracy. These reduce themselves to two—the scale on which the traverse survey is plotted and the closeness with which it can be checked. In general geologic surveying the scale of the field map ranges from 2 miles to 1 inch (1 : 125,000) to 1,000 feet to 1 inch (1 : 12,000). Now, if our sight is not more than $\frac{1}{2}$ inch long, when drawn in the notebook, an error of 1 degree on either side of the true line will fall within the width of a pencil line, or as close as we could draw an observation, however accurately observed and noted. But $\frac{1}{2}$ inch on a scale of 1 : 125,000 is 1 mile, and on 1 : 12,000 is 500 feet. These are distances which will rarely need to be exceeded in traversing on the scales indicated or on any intermediate scales.

In plotting courses the notebook may advantageously be held in the left hand with the fingers under it and the thumb holding the paper scale firmly on the page. The further end of the scale can be steadied by the little finger of the right hand, while the line is drawn with the pencil held between the thumb and two fingers. In order to avoid erasures, the line should be no longer than the sight is known or is estimated to be.

The closure error of traverses run in this manner by pacing, sighting with free compass, and plotting by coordinates, varies in my experience between 1 and 5 per cent of the distance run, according as the line followed roads or winding trails or over mountains without a trail. In any case where the data are part of a map they should be checked by more accurate locations. The surveys necessary to get the control should, however, be executed separately from the geologic study, so far as possible.

The geologic traverse, which is plotted in the field, is often second in importance to the deductions it immediately suggests. If the investigation has been conducted for the purpose of getting an understanding of the structure, the traverse has served a major object in the development of that understanding, for each observation of strike and dip, or of the occurrence and classification of an outcrop has been located as made. The plan of the structure and the data for constructing the cross-section of it have been delineated. And interpretation has gone forward according to the assembling of the facts, as it could not with mere verbal descriptive notes.

Objects of Survey.—In order that a particular geological survey should be conducted with efficiency to a result that shall satisfy its purpose, the methods of execution should be adapted to that end. This means that the geologist shall consciously classify his purpose and plan his method accordingly. It is convenient to distinguish reconnaissance, general, and special surveys.

Reconnaissance surveys are made under conditions which impose the requirement of large scope and allow only relatively short time. Thus a prerequisite of success is efficiency. But to be efficient one must be both trained and prepared for the particular study proposed. For this reason reconnaissance requires experienced men.

Any study may be begun by a reconnaissance, whether it is to be conducted in the laboratory or in the field, the purpose being to obtain the data on which to plan a more detailed investigation. From one point of view a college course is a reconnaissance of the field of knowledge for the purpose of discovering the branch or branches in which future specialization shall be undertaken. Or an Edison may test a great variety of materials to find that general class which is most likely to repay the labor of more thorough experimentation. Or an explorer may traverse an extensive country, gathering general information on which future journeys shall be planned. In each case the object is similar: to lay the foundation for more intensive work.

A geologic reconnaissance is, as a rule, a rapid survey of a region too large to be covered thoroughly. Preparation for it should include the study of what is already known and a digest of this in accessible form for the journey. What another has seen has a special interest in the light of his description and may lead his

successor to a further step. It is also true that the unknown is infinitely more difficult to observe than that for which we are somewhat prepared, however slightly. The fact is too evident to require elaboration and too often neglected to be passed over unmentioned.

Where surveys are to be carried out rapidly, but not hastily, system is essential. The kinds of observations to be made and the methods of making and noting them should be considered in advance. The observer, the methods, and the means should be coordinated and the work should be practiced.

In the field, in course of the reconnoissance, there is constant need of the exercise of selective judgment. The capacity to pick out the essential from innumerable and varied opportunities for observation is the prime qualification of a good explorer. And with this selective ability should go that understanding of facts which will enable the observer to recognize those that are of more than general importance.

Because haste is commonly imperative in reconnoissance and most of the observation must be incomplete, if not superficial, *it is necessary to pause occasionally with the definite purpose of doing something thoroughly*. That something should represent a critical fact, such as the thickness and normal sequence of strata, and it should be observed with all possible care. A few such observations serve as a framework on which to hang the less substantial ones and give permanent value to the whole result. The spirit of the explorer is usually impatient of delays for detailed work. He sees limits set to the wide fields he hoped to range, he is carried on by his own impetus; but if he wishes his work to stand future investigation or to be worth what it costs in time and money, he will take time to build some solid facts into its foundations.

The execution of a geologic reconnoissance should be intrusted only to a geologist fitted by physique, personal qualities, and experience, for the task. The exploration of Alaska, which has now been prosecuted with remarkable efficiency for 25 years and is passing into the stage of more detailed work, is an example of the wise application of that principle. It has been executed by picked men.

Personal qualifications fall under the four heads of physical fitness, mental fitness, morale and experience.

It goes without saying that an explorer should have a sound

body, but more than that he should have special qualifications, appropriate eyesight, for instance. A near-sighted man cannot advantageously observe the outlines, color distinctions, and detailed forms of mountains, upon which depend inferences regarding their physiographic history and structure. Whatever the environment of the proposed work may be, the geologist should consider himself as he does any other item of equipment and should see to it that he is physically fit.

Mental alertness is a prime requisite for efficiency under pressure of time and circumstance. With it should go decision. In practical matters these should be governed by common sense, and in scientific inference by the habit of toleration. The observer who is intolerant of alternative hypotheses will not maintain an unbiased opinion. The capacity to entertain several views or interpretations of partially understood and incomplete groups of facts is indispensable, if the work is to be sound. Mental alertness and mental honesty should go hand in hand.

As regards morale the explorer should have the pluck of an American and the self respect of a Chinese. It comes to the same thing, for the American's pluck is an expression of self respect, and the self respect of a Chinese demands similar determination. The two may be distinguished as self-reliance and reliability. Their combination, associated with cheerfulness, fair-mindedness, and kindliness, constitute 40 per cent of the qualities that a good explorer should possess.

If now we allow another 40 per cent, about equally divided, to physical and mental fitness, we shall have left 20 per cent of the sum of the qualifications of a well-equipped man, and this we must assign to training and experience. Both training and experience should be as broad as possible. However special the certain object of an exploration may be, there will always be many collateral, and often intimately related, lines of observation which can be pursued to advantage. Assuming that the major subject to be studied is the geologic structure of the Himalayas, for instance, the geologist should know physiography, stratigraphy, paleontology, and petrology, in addition to being specially grounded in the structures of mountains. His knowledge of the collateral lines may not be all-embracing, but he should know how to read the facts which they present, at least to the extent of being able to observe them and record them correctly and intelligibly. His command of auxil-

aries, if we may so designate related branches of knowledge, may advantageously be even wider, including the geography of the human races, social customs, and language. If his object be related to the resources of a region, with a view to their valuation, his grasp of the problem should include economics, commerce and financing. He is then, however, no longer primarily interested in structural geology, although that branch of observation may hold the key to the situation, as it does in the investigation of many oil fields. He has become a fully-equipped consulting geologist.

A specialist is not infrequently chosen for reconnoissance, breadth of study being sacrificed to intensive investigation. The situation which then arises is, however, an illogical one, since the habit of thought of the specialist is usually one which unfits him to observe comprehensively, in the large. Accustomed to laying bricks in his mental structure, he cannot build with great monoliths. The only specialist who can successfully cope with the problems of reconnoissance is a specialist in reconnoissance.

In the preparation of physical equipment the categories relating to clothing, bedding, food, shelter and transportation are intimately related with one another and with the conditions of life in the region to be explored. Each case must of necessity be considered in the light of what is known or may reasonably be inferred regarding the circumstances. Experience, however, dictates one principle of general application. The explorer may better adapt himself and his ways of doing things to those of the country and people than to try to convert the people to those which seem to him handier. This applies especially to equipment which must be handled by the natives of the country. I have known an expedition to break down because pack saddles, made by a saddler who never saw a burro, caused sore backs, where the native packers could have made good with their rude but accustomed outfit. Even personal habits with respect to food, clothing, and bedding may wisely be modified voluntarily, but always within the limits essential to health and efficiency.

The discussion of preparation for reconnoissance has diverged somewhat from the purpose of the chapter, the application of structural geology to certain aspects of geological work, but the diversion is, perhaps, not inappropriate, since reconnoissance is an

important method of survey by which to ascertain the larger features of geologic structure.

A *general survey* may be so described because, within the area which it covers, it is supposed to include all aspects of the local geology. It differs from a reconnoissance in the two respects that it is thus all inclusive and that there should be sufficient time allowed to permit the geologist to assemble all the facts bearing upon the problems he discovers. Good examples of this class of work are to be found in the folios of the Geologic Atlas of the United States.¹ Those enumerated in the subjoined list illustrate a great variety of general surveys, in areas where the problems are of broad geologic interest and the geologic structure plays an important rôle. It is to be noted, however, that work of this character is mainly descriptive. It thus differs from what we may call monographic study, since the latter purposes to carry on the investigation of the assembled facts as a research into their more fundamental relations and causes. The general survey thus stands between the preliminary reconnoissance and the more or less final monograph.

The methods which may be employed to attack the study of a district with reference to its structure are more detailed and complete in a general survey than in a reconnoissance. The reconnoissance, however, may well precede the detailed survey, and the methods of field observation may therefore be stated in sequence. They would be practically the same at first for both objects.

In the hypothetical case to be considered, the geologist is approaching and entering a district where the rocks are so exposed that he may observe their general character and attitude. He will begin to ascertain that he has to deal with sedimentary or igneous or metamorphic rocks, or with more than one of these classes, and the possible types of structure will be suggested.

Even before he has recognized the rocks, while he is viewing them from a distance, the physiographic aspect of the country

¹ See, for instance: No. 30, Yellowstone National Park, Wyoming; No. 31, Pyramid Peak, California; No. 36, Pueblo, Colorado; No. 62, Philadelphia, Pennsylvania; No. 71, Spanish Peaks, Colorado; No. 78, Rome, Georgia; No. 83, New York City, New York; No. 94, Brownsville-Connellsville, Pennsylvania; No. 131, Needle Mountains, Colorado; No. 139, Snoqualmie, Washington; No. 142, Cloud Peak—Fort McKinney, Wyoming; No. 149, Penobscot Bay, Maine; No. 151, Roan Mountain, North Carolina, Tennessee; No. 196, Phillipsburg, Montana.

has given him a clue to the later history of earth movements. His eye ranges from canyons to high-level, old valley floors and from these up to summits which, by their acute or rounded forms, by their equality or inequality of summits, suggest the degree of preservation of an earlier topographic phase. If not these particular features, then others may be noted and questioned as to their meaning. It was thus that from a tower of the Great Wall of China, I first scanned the Wu-t'ai-shan, a fore-range of Tibet, and began to read the physiographic history of that great uplift.¹ (Fig. 97.)

Before we reach the point whence a broad view may be had, the route of ascent will lie in a canyon, or up a spur, or over a slope, but in any case must pass some outcrops of rock, upon which observations can be made. Any geologist will pause to break the rock to ascertain its character. A structural geologist should examine its structure, taking the strike and dip of the stratification or of obvious joints. These afford the first suggestion of the directions in which forces have acted to produce the structure of the mountain.

As one proceeds, notes of this suggestive character accumulate, but they lack coordination unless their mutual place relations have been determined. It is here that the habit of surveying is found useful, particularly the habit of carrying a traverse by pacing and compass. By Ford or horseback is a much less satisfactory mode of progress than walking, where the object is to observe rocks or landscapes. They are passed too swiftly and the inertia opposed to dismounting is too great. Assuming that the geologist is afoot, he should begin to pace from the first point of observation, in order that he may locate that structural note with reference to all those which are sure to follow. Beginning thus at any undetermined place, the traverse line will be in the air until it is tied in to a crossroads, stream fork, or mountain peak, that is to some identifiable feature. By continuing it, this object will eventually be accomplished and all the points of observation on that line of route will be known.

The necessity of coordinating any structural observation with others by determining the relations in space should not need emphasis. Only by so doing can the forms and dimensions of structures be ascertained. Verbal notes lack this essential state-

¹ "Research in China," vol. I, part I, p. 208, Plate XXX.

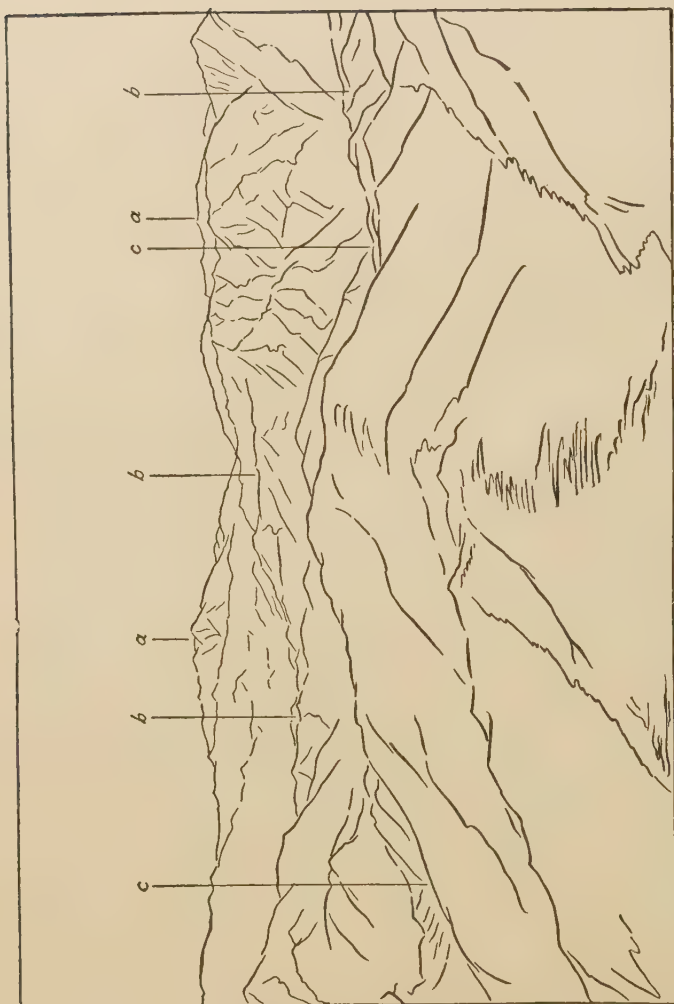


FIG. 97.—View of the Wu-t'ai-shan Range, Shansi, China, showing topographic features and their relation to the stages in its development. *a*, the oldest stage, an ancient peneplain forming the highest summits; *b*, ridges representing the level of erosion following the uplift of the mountains to their present level.

ment of place relations and therefore cannot take the place of the graphic notes that are linked together by the traverse line.

Circumstances may preclude the possibility of plotting graphic notes continuously in the form of a traverse, while yet permitting pacing and compass sighting. The distances and courses may then be set down in systematic notes, to be plotted at the earliest opportunity. If the traverse be interrupted it should nevertheless be renewed in such sections as conditions permit. Afterwards it may very likely be found that those sections contain all the definite information obtained.

If a piece of traverse cannot be run to a known point, the position of any station on it may be fixed by sights to two points whose positions are known. Greater certainty can be secured by observing three points. The observed compass bearings can be plotted on transparent paper as lines radiating from a point and placed over a map. By shifting the paper about till each of the lines passes through the point to which it was sighted, the location of the station sighted from becomes known. Triangulation methods of this type are peculiarly helpful in reconnoissance where the requirement of rapid progress is all important. There is then grave danger that the observer may be stampeded into neglecting some valuable observation because he feels that it will not be possible to locate it. He should make it nevertheless and, traversing to some point of outlook, he may fix it by three sights.

It is a common custom among geologists to have a topographic map enlarged photographically in order that it may be big enough to permit of making notes directly on the enlargement. There is an apparent gain in convenience, which may be real enough to justify recourse to the method in individual cases, but there is a real loss which is often not so apparent. The supposed gain lies in the assumption that points at which observations are made may be located on the enlarged map without the labor of making a traverse, but with sufficient accuracy to satisfy the geologist's purpose. The conditions are, however, not favorable. The map, however accurately drawn for its original scale, is no longer accurate as to positions or complete as to details when enlarged. The generalizations which were required by the smaller scale are too obvious on the larger. The omissions become sources of confusion. The features of the map have lost much of their individuality by the broadening of the lines.

To these drawbacks is to be added the more serious one that the geologic facts do not stand out clearly from the maze of lines on the map as they do from the manuscript plot of a well-balanced traverse. The object of taking the graphic notes is lost by making them over other lines, and this loss is most felt during the progress of investigation.

Assuming that the geologist plots his observations of the characters, strikes, and dips of rocks in relation to a traverse line, which he runs as he goes, he sees developing on the notebook page a plan of the structure. The rocks, their variations, likenesses, differences, and significance concern him most. But their attitudes, which express mass relations, are next. Let the section display a sequence of sedimentary beds which exhibit a decided dip. They may be right side up or upside down, so far as the dip determines. The dip changes, becoming gentler or steeper, or the strike swings, in successive observations. A flexure or fold is indicated. Attention is directed to locating it and the axial line is looked for. Its position is an important fact because it sets a limit to the section which can be seen. Its character, whether synclinal or anticlinal, determines whether we have been ascending or descending in the sequence. Its pitch fixes the succession of the strata in a longitudinal direction to right and left.

In approaching a large, possibly complex, fold we may observe a little one, perhaps no larger than a hand specimen. Therein lies a clue to the attitude of the larger structure, which may be too large to observe directly without much labor, for it is a rule that *the pitch of minor folds agrees with that of the complex fold of which they are part*.¹

The magnitude of the fold is not discernible, as a rule, at the axis. Any sharp fold appears small if we can see only the immediate bend. The size depends on the length of the limbs and the thickness of the strata. We may have observed the latter in approaching the axis and know, accordingly, the importance to be attached to the fold.

On passing the axis of a fold, whether it be an anticline or a syncline, the strata should repeat in inverse order to that in which they were encountered in approaching it. Thus we may have noted the beds in the order *a, b, c, d*, but beyond the axis they

¹ PUMPELLY, RAPHAEL, and DALE, T. N. Geology of the Green Mountains. U. S. Geol. Surv., *Monograph XXIII*, p. 157, 1894.

should recur in the order *d, c, b, a*. If the fold be a simple, unbroken one, the sequences should be the same on opposite limbs. If they are not the same, we have crossed a fault or an unconformity.

The distinction between a fold, a fault, or an unconformity is not always clear in a single section and may remain obscure until the line of outcrop, along which the evidence must be sought, is carefully studied. The criteria to be looked for are stated elsewhere, pages 225-227.

We are *en route* to a summit from which we may obtain a general view. We carry the traverse to the point and thus know where we are with reference to the rock masses which have been crossed. We know their strikes and dips. We can therefore identify them with the ridges or valleys to which they give rise and can interpret the landscape in terms of its anatomy.

The explorer who thus looks out from some peak that commands his unknown route may feel the thrill of discovery. He may never see that view again. It therefore behooves him to study it thoroughly, to exhaust its indications, and to record his observations in more or less elaborate outline sketches, with bearings and verbal descriptions. It is hardly possible to overestimate the value of carefully noted facts, which later serve to bring the scene clearly to mind.

The ability to read a landscape in terms of its history and underlying structure now serves a geologist as his knowledge of German should in reading the classic work of Heim. He will recognize three classes of intimately related facts: the effect of the observed rock masses on differential erosion; the survival of areas of an older topographic phase, or of several such; and the activity of warping or faulting during the more recent geologic epochs.

With reference to differential erosion he will trace out the extensions of those strata which he has noted during the ascent, and they will furnish the ground work of his inference beyond what he can definitely recognize. Had he arrived by aeroplane or, what amounts to the same thing, without observing the visible facts along his route, he would be without this firm foundation. When, however, he knows that a certain sandstone maintains a certain ridge, he can follow the sandstone by the ridge. Or he sees that a certain sequence of shale and limestone gives rise to extensive valleys, as observed in crossing them. Then similar valleys in the same region are presumably underlain by that group of strata.

In such inferences there is always the possibility of error because the stratigraphy is, as yet, only partly known, and there is the probability that there are two or more sandstones or several groups of weaker rocks. Alternative hypotheses thus arise. They stimulate observation. We begin to look for differences as well as likenesses.

The concept of differential erosion dates from Hutton, who first recognized it prior to 1785, and the application of it to the study of structure has been more or less consciously the habit of every geologist who has pondered the relations of erosion to the rocks in the field. It is otherwise with the recognition and use of an old topographic surface as a datum by which to identify changes of level and attitude of mountain masses. The names of Powell, Gilbert, Davis and Hayes are associated in the development of that method.¹

As we look abroad from our point of vantage, we see what we may have observed during the ascent, that the valleys widen by steps. At least, that is a common habit of valleys in most mountain ranges. There is the inner canyon, distinguished by narrowness and the comparative steepness of the slopes. There are terraces or terrace remnants with leveled floors of rock beneath soil or gravel. There are sometimes two or more such evidences of an old valley floor. And there is the upland, which represents the more or less completely finished peneplain or mature surface of an earlier topographic cycle. These are witnesses of the intermittent activity of the uplift, which has raised the mountain range where formerly there stretched a lowland.

One of the most perfect examples of an uplifted surface is the peneplain which has been traced over the Appalachian province by Davis, Hayes, and Campbell. It was a very flat plain before it was warped and it has been warped to a very broad arch, without any notable local disturbances. It has become a classic example, by reason of its accessibility and of the thoroughness with which it has been described. Consequently it is the established type of a warped, topographic surface. But because it was so flat a plain, because it has been so broadly warped, it is not representative of

¹ POWELL, J. W., "Geology of the Uinta Mountains," 1876; GILBERT, G. K., "Geology of the Henry Mountains," 1877; DAVIS, W. M., "Rivers and Valleys of Pennsylvania"; HAYES, C. W., and CAMPBELL, M. R., "Geomorphology of the Appalachians," 1894.

many other surfaces of erosion, which were not so perfectly finished and which have been more sharply warped, bent, or faulted on a smaller scale.

It is always fair to ask a landscape: what are your oldest features and where do they survive? The Cascade range of Washington, the Sierra Nevada and Coast Ranges of California, the Andes of Patagonia, the Alps, the Apennines, the Carpathians, and the mountains of central China, have all answered by presenting a hilly surface, having a relief of several hundred feet, but representing a mature surface of erosion, as their oldest surviving feature. They bear it on their broader summits, of course, but they also exhibit it on slopes which may be gentle or steep, and it sometimes extends down beneath wide valleys, from under which it rises again on the other side in true synclinal fashion. Where a slope is faulted, it can be traced like a sedimentary stratum across lower hills to the face of a mountain range, against which it ends. Its further extension is to be sought on the summit of the range.¹

The identification of an erosion surface, which is no longer at the level or in the attitude in which it was formed requires discriminating care. Alternative explanations of the apparently older peneplain should be hospitably entertained and tested. More than one view of the landscape should be studied. The flat light of midday should be avoided, because it runs the distinctive shapes together, and the long shadows of morning or late afternoon should be awaited, because they bring out the forms.

Is yonder broad, rather flat-topped mountain a mass which carries a remnant of a peneplain? If so the topography of the summit should agree in development with that stage of planation. The soil should be deep, leached, and well oxidized. The valleys should be wide, filled with alluvium, and occupied by meandering streams. The low, soil-covered elevations should consist of the harder rocks and the softer rocks should be buried. This is a group of criteria which pertain to a lowland plain or to a mature surface of erosion. They are decidedly not appropriate to a mountain top. If they all are present and characteristically developed, the inference of uplift since the surface was eroded is well sustained. It becomes conclusive when supported by observation

¹ WILLIS, BAILEY, Report on an Investigation of the Geological Structure of the Alps, Smithsonian *Miscellaneous Collections*, vol. 56, No. 31, pp. 7-9, 1912.

that the general flattish surface is eroded across rocks of unequal resistance, is in fact a true peneplain or mature surface of erosion, such as can form only at a low elevation.

We feel less sure when the flat-topped mountain is a table mountain or mesa, composed of flat lying strata, and perhaps surrounded by a rim-rock cliff. Then it is evident that the structure of the mass is favorable to the development of the form. Wind blowing away soft shale, for instance, may leave a hard table of sandstone, which simulates a plain of old-age erosion. This obvious case may serve to suggest the alternative explanation which rests on the influence of structure. When the topographic surface coincides with a rock surface, which is of such a character that it may be the cause of the topography, the inference of that causal relation is more direct than any other. It should therefore be tested by an appeal to the actually operative agencies of erosion, to determine whether they are competent to produce the observed facts.

In my experience, small topographic forms are often related to and due to the characters of small rock masses. Extensive topographic flats, on the other hand, are usually not the result of rock character, because the latter is too local and changeable.¹ The coincidence is found to be more apparent than real when the strata are traced over a wide area. The outcrops of the bedding planes are then often seen to cross the plain of erosion, with which the dip of the strata makes a small angle.

That long smooth slope which descends from the even-topped ridge to the flood plain of the valley over there does not explain itself at once. Accustomed as we are to consider all valleys as valleys of erosion, that is, as excavated in softer rocks, we would usually call the slope an erosion slope. Its story is then very simple. As the general upwarping of the region progressed and the streams sank their channels into it, there developed a canyon wall, which receded to a mountain slope and became ever lower as the cycle of erosion progressed toward its more advanced stages. In homogeneous material, such as a thick body of shale presents, the slope will tend to be the same along any given contour, especially if one looks along the lines of spurs. From valley to summit, however, the profile will increase in steepness, according to a curve

¹ SMITH, G. O., Contributions to the Geology of Washington. U. S. Geol. Surv., *Prof. Paper* 19, 1903.

that is *concave upward*. If the material be not homogeneous, a mass of schists intruded by dykes for instance, every difference of resistance to the processes of weathering and erosion will be brought out by an accent of relief, for differential erosion has been active ever since the canyon wall was bared. The ravines which score the slope will also be significantly developed. They will have grown like gullies, with vigorous growth of the little trunk gully, but only very slight development of laterals, and the latter will tend to flow decidedly down the slope, instead of along it parallel to the strike of the bedding. The junctions will be acute-angled, not right-angled.¹

The ridge crest may be of the Appalachian type—level, even, and far-stretching, interrupted only by occasional wind or water gaps—and it will then be recognized as the intersection of the slope with an ancient plain. Or the ridge may be broad and somewhat hilly on top, presenting a surface which may be interpreted as very young or very old or a combination of young features with aged ones. In some mountains the summits are all acutely sculptured by frost and ice and water, till there is nothing of the preceding cycle left, save perhaps an approximation of peaks to a common level.² The actual features are then all young. Elsewhere a broad ridge partakes of the character of an uplifted peneplain and exhibits its aspects. This is very commonly the case in the Coast Ranges of California, the mountains of Central America, and those portions of the Andes with which I am familiar.³ It is also a feature of common occurrence in Europe, in the active young ranges of the Alps, Apennines, and Carpathians. Or the young headwaters of older streams may have pushed their canyons back into the remnant of the peneplain so as to combine recent and ancient features in one landscape. Such an association is of very general occurrence, where the modern cycle has not yet destroyed all the features of the older.

¹ This type of erosion slope is well illustrated along the Allegheny Front and elsewhere in the Appalachian province. See, for instance, the mountain on the east of Poor Valley, Mercersburg quadrangle, Pennsylvania.

² WILLIS, BAILEY, Contributions to the Geology of Washington. Deformation and Physiography of the Wenatchee-Chelan District, Cascade Range. U. S. Geol. Surv., *Prof. Paper* 19, plates, 1903.

³ WILLIS, BAILEY, Physiography of the Cordillera de los Andes. Intern. Geol. Congress, 12th Session, *Compte Rendu*, pp. 733-756, Toronto, 1913.

Let us now look again at that long smooth slope which connects the valley and the ridge over there. Is it necessarily an erosion slope, sculptured in its present position? Or is it perhaps an older surface, tilted or bowed up into an attitude which is inconsistent with its original form? If the latter be the case what is the effect of the work of erosion in remodelling the surface? Questions such as these cannot lightly be put aside without weighing the evidence for or against the hypotheses they suggest. They first took definite form in my mind while studying the eastern shore of the Adriatic from Fiume south, and I have since found them very fruitful.

Consequent streams flowing down a tilted peneplain resemble those which develop as gullies and ravines in a slope due to modern erosion. They also flow straight from ridge to valley. But they are not so simple. Rivers of the earlier cycle existed there before the consequent streams were born, and the older generation had long since become adjusted to the structure. In most cases that adjustment had resulted in channels which run parallel with the trend of the range, at right angles to the courses of the consequents. When uplift occurs, the older streams are usually not accelerated to a degree sufficient to enable them to compete with the newly developed consequents, and they are therefore captured by the latter. The resulting river systems, or rivulet systems, are characterized by a rectangular plan and flow through valleys and canyons, which differ in development as maturity differs from immaturity.

The most conspicuous example of a tilted surface is the western slope of the Sierra Nevada of California, which has been described by Whitney,¹ Diller,² Gilbert,³ and others. It is, however, not a simple peneplain and its streams are not simple consequents combined with an older system of adjusted rivers, because lava flows have modified both. A smaller example, in which the tilted peneplain and the combined drainage systems may be seen, is found in Ben Lomond ridge, which extends north from Santa Cruz, California, to a distance of some 15 miles and rises 2,500 feet above the Pacific in a distance of 6 miles.⁴

¹ WHITNEY J. D., Auriferous Gravels, of the Sierra Nevada, Harvard Coll. Mus. Comp. Zoo. *Memoirs*, vol. 6, pp. 63-64, 1880.

² DILLER, J. S., Tertiary Revolution in the Topography of the Pacific Coast. U. S. Geol. Surv., *Fourteenth Annual Report*, pp. 408-410, 1892-93.

³ GILBERT, G. K., *Science*, vol. I, p. 195, 1883.

⁴ Santa Cruz atlas sheet, California, U. S. Geol. Surv.

The surface of a tilted slope is usually deeply gashed by consequent canyons. The interstream areas, however, may preserve the aspects of the older surface, whether it was a well-developed peneplain or a mature topography of greater relief. We search for those areas and then proceed to question them as to their identity, their more or less intimate association with rock structures, and other suspicious relations. If they are not too much wasted by recent erosion they will bear positive testimony to their former state.

A form which is rarely, if ever, produced by differential erosion, is a long curve extending from valley to summit and *convex upward*. It may appear in transverse or in longitudinal section, and commonly in both, if at all. One inference is that it is a denuded anticline, which has been stripped down to a resistant bed and is an exposed fold in sedimentary rocks. But that guess gives way at once where such profiles are shown by hills of metamorphic and intrusive rocks, as is the case in the Coast Range of California. That range is traversed by great faults, which exhibit effects of very powerful compressive stresses and of greater horizontal than vertical displacements. The mountains adjacent to these faults are bowed up in consequence of internal shearing and the older topographic surface arches over them in an anticlinal form.

Thus from our vantage point on a summit, at the end of a traverse which has enabled us to locate certain facts in their proper relations, we cross-question the landscape and from its responses to various questions we obtain some idea of the structures within our view and of the relative activity of erosion as compared with that of warping, folding, or faulting.

There is one test question which every feature of a landscape should answer: *Do you fit into the modern scheme of landscape sculpture? If not, why not?*

If we have lingered on our vantage point until the shadows lengthen toward the east, as it is wise to do, the run to camp will be made without further observation of geology, except perhaps of a locality to be visited on the morrow. Supper and the pleasant inertness that encourages smoking follow. It is not a time favorable to constructive thinking, but it is well to chew the cud of reflection in preparation for early morning thoughts. So supplied, the mind works while we sleep and presents us on waking with new suggestions, sometimes with the solution of a problem that has been particularly baffling the evening before.

The point I wish to make in this stage of the description of field methods is that thinking is appropriate to field work. Facts are to be scrutinized and classified. Gaps in the chain of facts are to be discovered and noted, that they may be filled when opportunity occurs. Groups of facts are to be examined as to their meaning and are to be placed in relation to one another as elements of an hypothesis. Hypotheses that will explain all the known facts and suggest lines of investigation are to be thought out.

Physiography takes first place in preliminary studies of structure because its facts are so large and so widely displayed. But we must turn to stratigraphy for the facts that enable us to interpret structure with an understanding of details. In an unknown field the immediate obligation is to ascertain the normal sequence in which the strata were laid down.

The primary condition of observation of strata is that they shall be exposed and the second is that the exposures shall succeed one another across the strike with as few gaps as possible. Different types of country offer very unlike opportunities and no rule can be laid down, but the geologist may save time by reasoning from the obvious topographic facts. A deep mantle of residual soil is avoided in a region of rejuvenated mountains by following the young canyons. Alluvium in an aggraded valley may drive one to follow the ridge tops. The windward side of a hill, as indicated by the lean of the trees, is more apt to show outcrops than the lee side, in an arid or semi-arid country. Glaciation may have buried everything except occasional rocks, for which one must make a systematic hunt. Whatever the conditions of accumulation of soil, it will somewhere have failed to cover the strata, and an intelligent analysis of the processes that have been at work will promote the discovery of the localities where the desired information can be obtained.

Measuring the thickness of strata is a question of gross measurement or of detail. For gross approximations, I resort to the paced traverse and plotted field map, which gives the observer complete freedom of movement from outcrop to outcrop, yet furnishes constantly the opportunity to ascertain at any moment what the observed section is. There is a very great advantage in instantaneous results over those which are postponed to some future time, when instrumental or written notes can be worked up.

Detailed studies for thicknesses and sequence are usually so

related to requirements of precision that no pains will be spared to get accurate and connected results. A paleontologist friend, who measures as he collects, carries a 5-foot stick which he lays across the beds. Adding up items of thickness and correlating them with fossils, he knows at the end of a day's work the magnitude and the ages of the formations he has been over. Having adjacent sections in mind, he can compare, can infer the thickening or thinning of strata, may be directed to a concealed unconformity or fault, and always has at hand a mass of facts that make him a disconcerting opponent in debate.

Where strata are nearly horizontal, the factor of elevation of outcrop becomes more important than that of horizontal distance. We may then disregard the latter and draw a profile on which outcrops are placed according to their altitudes, as determined by repeatedly sighting on a level and multiplying by the height of eye, or by taking slope angles and paced distances, or by aneroid with proper checks. The variety of possible methods for getting the thicknesses of strata is great, and the main thing in field work is to know which to choose and how to pass from one method to another to secure the maximum efficiency.

Observations of thickness and sequence are simply means to an end, facts from which to infer the past history of the mountain region, including that of its structure. One of the most important distinctions is that between marine and continental deposits. The lines of inference as regards the structures are markedly different in the two cases. In marine beds, thicknesses are generally uniform or vary gradually. The succession of strata is apt to be the same over wide areas. It is possible to establish standard sections and to reason from their general continuity that discontinuity is to be explained by some peculiarity of structure, such as a fault. Alternatives are to be considered, of course, such as a disconformity, due to marine scour, or an actual unconformity. But the probability that the original sequence of strata was invariable over large areas simplifies the study of the structural problem.

It is otherwise with continental deposits. They are characteristically lenticular and variable. The conglomerates are most so, the sandstones less so than the conglomerates, the shales least of the three. Correlations are therefore more certain when made on shales than on sands and surer on sands than on conglomerates. Yet the monotony of shales and their prevalence in many sections

reduces their value as lithologic markers. In drill logs sands are most often the basis of correlation, and their tendency to lenticular distribution as bars or in alluvial cones or as æolian deposits is the cause of much uncertainty. The surface on which continental formations are laid down is also less regular than that on which marine sediments accumulate, and the inequalities sometimes result in contacts that look like displacements. A Pliocene conglomerate in contact with a nearly vertical face of Miocene shale has been mapped in California as a normal fault in an oil field. It is simply one wall of an aggraded canyon of erosion in the shale.

Thus it becomes important to distinguish marine stratigraphy from continental, very much as we differentiate algebra from calculus, and to recognize the very much greater difficulty of stratigraphic and structural work in the latter class of deposits. The matter has assumed importance because continental formations are common in many oil fields.

The stratigraphic sequence underlies all interpretations of structure, just as spelling is the basis of intelligible writing, and the first task of the geologist in an unknown region is to ascertain it. More often than not in my experience the study of the structure has of necessity been carried on concurrently with that of the succession of strata and consequently with an element of uncertainty. The degree of difficulty varies very greatly. In some districts, as in the Paleozoic of New York where the standard sections for America have been established, the formations lie in regular order, unequivocally right side up and as they were deposited. There the succession of organic forms may be determined and, although there may be gaps in the record, we need never doubt but that we observe the true sequence as we pass from that which lies below to that which overlies, from older to younger.

It is otherwise where formations are overthrust or overfolded. We can no longer be sure, in the absence of fossils, which is truly upper or lower among the strata, and our structure remains capable of more than one interpretation. The complexity increases with the occurrence of intrusions and with metamorphism. It may then take years of patient research to unravel the tangled skein.

Descriptions of some of the simpler types of structure follow, with suggestions of methods of observation.

ANALYSES OF STRUCTURAL TYPES

I. Strata Gently Inclined, Plateau Type.—Climate arid to semi-arid; vegetation sparse; wind erosion predominant on flats, leaving residual deposits of gravel and coarse sand and creating drifted formations in lee shelters; surfaces of resistant rocks stripped; incrustation results from percolation, solution, and evaporation, producing calcareous caps, which the wind undercuts; rocks resist weathering in the order: (1) quartzite, siliceous schists, siliceous limonite, and other fine-grained, firmly-cemented rocks of uniform color; (2) limestone and calcareous shale; (3) granite and sandstones; (4) incoherent beds of sand or shale.

The flat-lying strata pass into monoclinal flexures and high-angle faults. The simple structures can be traced by bands of color or of vegetation. Minor folds and crushing are found on faults. Drag folds indicate the direction of displacement. Typical region, the Colorado plateau.

II. Monoclinal Dips, Cuesta Type.—Climate arid to semi-arid; conditions of weathering and development of relief as under I. The dips are usually under 45 degrees and the topographic form is a ridge with one long dip-slope and one steep, scarp-slope. The internal structure of the ridge is simply monoclinal. The major structures, including desert valleys and ranges, are fault-blocks, which are bounded by high-angle faults of great displacement and notable length. The fault-blocks are commonly rotated so that the upthrown edge forms the ridge, whereas the downthrown side lies under the valley fill. An effect of rotation is to cause the plain to cross the strata diagonally to the strike and dip. Thus the oldest beds may appear only under one corner of the scarp-slope, while the youngest are to be found on the opposite corner of the dip-slope. The scarp-slope may exhibit normal faults of the landslide type, either as elements of major step-faulting or as minor effects incident to reverse faulting.

In arid and semi-arid regions of the plateau or cuesta type pre-Pliocene erosion surfaces are frequently so modified by windwork that their recognition is difficult.

The typical region of the cuesta type of structure is the southwestern United States (Trans-Pecos, Texas, to southern California). The typical cuestas of stratified sediments pass by the occurrence of intruded igneous rocks into the Basin Range type, which is also characterized by block-faulting.

III. Simple Folds, Ridge Type.—Climate humid, windwork lacking, erosion by solution and corrosion; relief due to unequal resistance of sandstone, shale, and limestone, ridges following sandstone outcrops and valleys being developed on limestones or calcareous shales; siliceous shales making hilly belts. Ridge crests even, broken by wind gaps and water gaps, demonstrating a dissected peneplain and the adjustment of streams to structure in consequence of relatively recent upwarp.

Under these conditions each well-defined formation is associated with a distinct topographic feature, a ridge or valley of greater or less magnitude. The topographic plan and the structural plan coincide and the continuity of one indicates the continuity of the other.

Anticlines are recognized by divergent dips and by the greater age of formations next to the axis. Synclines present convergent dips and younger strata on the axis. Where the strike runs straight the limb of the fold is straight in a horizontal direction, but may be curved in any other. Where the strike curves the fold rounds toward an axis and the strike may turn around it through any angle up to 180 degrees; but the dips must continue opposite, either anticlinally or synclinally. Simple folds do not make corkscrew twists.

The method of surveying cross-sections is appropriate to the study of such structures, whereas longitudinal tracing of outcrops is usually both unprofitable and unnecessary. Given a topographic map, the formations can be traced between the tie points according to the plan of the ridges; if there be no adequate map, the ridges and the strata can be located between sections by compass triangulation.

Structural study of this kind is so very simple that it contains a psychologic danger: we are apt to assume that the folds are simple, when in fact they are not. The sections and the landscape should be constantly scrutinized for variations in stratigraphy and for inconspicuous faults.

In the Valley of Virginia there is a quartzite ridge which is cut across by a brook. There is a space of perhaps two hundred yards in which there are no outcrops. Beyond the brook the ridge continues, but lower and broader. Furthermore, it consists of dolomite. An immediate inference is that the brook flows on a fault. There is, however, no evidence of faulting in the section, except that the quartzite and the dolomite are lined up on one and the same strike. Examination showed that the dolomite contained sand grains and the brook flowed over calcareous sandstone, which yielded more readily to solution than the dolomite or the quartzite, and therefore had become the line of the brook's channel. Here was a gradation from a sandstone, which had contained but little lime and had been silicified to a quartzite, through a more calcareous sandstone, which contained too much lime to remain coherent, to a dolomite, which contained a little sand. We had the transition in sediments from an old Cambrian sandbar into calcareous ooze, but not a fault.

Elsewhere a change in form of a ridge crest, from a sharp edge to a broader flat, was due to a thrust which brought Cambrian sandstone in contact with Carboniferous limestone.

Wherever topography is etched with nicety to coincidence with structure, there variations in topographic forms become suggestive of corresponding accidents of structure.

In the United States examples of simple folding are well illustrated in central eastern Pennsylvania, and West Virginia, as shown by the classic work of H. D. Rogers or by the Piedmont, Pawpaw-Hancock, and similar folios of the Geologic Atlas.

IV. Simple Break-thrusts, Ridge Type.—Simple folds are apt to pass into simple thrusts by a slight change in form of the folds. Symmetrical anticlines change along the strike to unsymmetrical ones with a short, steeply dipping limb opposed to a long, gently dipping one (step folds) and the shearing couple produces an overthrust.

The classic examples of this structure occur in the valleys of southern Virginia and eastern Tennessee, where the structure is of pre-Mesozoic age, the dissected peneplain has been warped up since the Eocene, and the existing relief is an effect of differential erosion. The conditions of fieldwork are the same as in the region of simple folds further north, but with the additional requirement that the thrusts shall be traced along the strike, in order to establish the points at which the formation boundaries terminate.

It may happen that a thrust is encountered in running a section across a series of simple folds. The change in structure is indicated by the change in sequence of the beds. In folds the succession repeats in inverse order beyond any axis. On passing a thrust the sequence repeats in the same order. Sometimes the thrust is preceded by an anticline and possibly by an overturned anticline, but that warning of the approach to the thrust is not always present.

V. Closed and Isoclinal Folds.—Again it is assumed that the structure developed during a period which antedated the actual uplift and that the relief is sculptured according to the resistances of the rocks. The topography may then be found suggestive, but as the geology increases in complexity, the significance of that suggestion diminishes in importance. Let whatever value it may have be given to it, there will remain the major part of the structural problem to be solved by investigation of the details of distribution and by study of the minor structures.

The first step toward the solution of any really difficult problem is the making of a map showing the distribution of the rock groups and individual formations. It will also show observations of strike and dip. If the sequence of formations is known, their plan, as delineated on the map, goes a long way toward demonstrating their underground relations, and tentative sections may be drawn as an aid in visualizing the structure. It is more than likely that the first essays will raise new problems, which can be answered only by more intensive field work. We may anticipate some of them.

There is a series of sedimentary strata which is tilted and bounded by faults. We do not know which is the bottom and which the top of the series, since in complex movements masses may be overturned or overfolded. Evidence may be found on bedding planes in the form of ripplemarks, mud-cracks, trails, or burrows, which present their positive or true shape on the upper surface of a bed, but are represented by a negative or cast on the lower surface of the succeeding stratum. Shales, especially thin layers of shale between sandstones are the most favorable surfaces for such evidence. Fossils, which may have been rolled, should be accepted as evidence only with reservation.

Mechanical details are more likely to be found and are therefore of more general use than surface markings. They are joints, minor folds, and schistosity.

Let it be assumed that in close or isoclinal folds we cannot distinguish between anticlines and synclines. The dip may be anything from a low angle to verticality. Where the strata are right side up, an upper bed will have moved toward the anticline and a lower bed toward the syncline. If the strata are overturned, the lower bed will have slipped toward the anti-

line and the upper toward the syncline. The anticline will be up the dip, the syncline down it. Therefore, if we can determine the direction in which the strata have moved past one another, so that we can tell which moved up toward the anticline and which down toward the syncline, we can ascertain whether the strata are right side up or overturned.

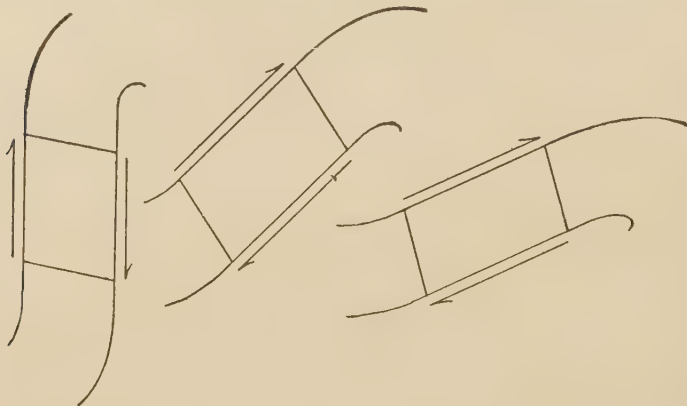


FIG. 98.—Normal limbs of folds, showing the position of shear planes developed according to the law of the strain rhomb.

Joints which have developed almost at right angles to the bedding are common in such cases. Whatever the departure from a right angle may be, one can distinguish the obtuse and acute angles of the rhomboidal blocks and may apply the rule: The acute angle between a bedding plane and a joint plane points like a blunt arrow in the direction in which the adjacent stratum has moved past the one in which the rhomb is situated. The argument is that the displacements of the bedding planes on each other constitute a shearing couple, in response to which the rhomb has developed from what would otherwise be a rectangle. The method originated with Van Hise and Leith, who designated it the method of the strain ellipsoid. (Figs. 98 and 99.)

We may push the application of the strain rhomb a step further. It very commonly happens that blocks are triangular and are bounded by a bedding plane and two joint planes. In hard, brittle rocks two of the angles of the triangle will approximate 45 degrees and the third will be a little more or less than 90. In softer rocks one angle may approach 30 degrees, another 60 degrees, and the third 90 degrees, being either more or less. The joints usually differ in degree of development. There may be two or three sets of them. Let us designate them in the order of their distinctness 1, 2 and 3, and let the bedding plane be 4. The following assumptions and reasoning may then apply, if the case is that which is shown in the diagrams. (Fig. 100.)

The bedding planes, designated by 4, have been planes of movement, since they bound strata which have been bent. Any pressure exerted against them was therefore resolved into components, parallel and perpendicular to 4. The parallel components on opposite sides of the stratum, forming a couple,

produced a system of shearing planes, designated by 2, which correspond to the distortion of a square into the strain rhomb. The perpendicular component, if sufficiently intense, caused two sets of maximum shearing strains oriented at angles amounting to anything from 45 to 60 degrees from its direction. Parting of the rock along these two planes of maximum shearing

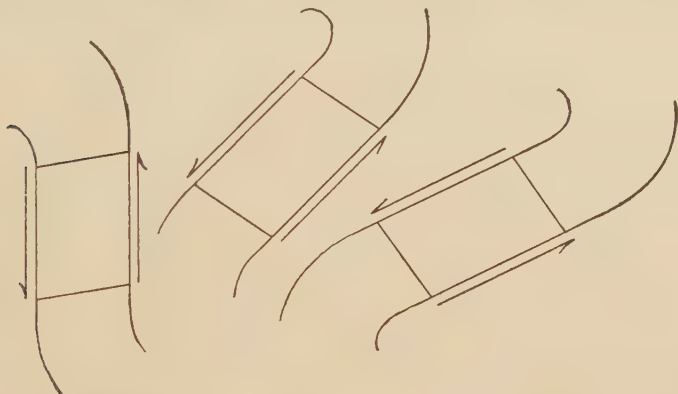


FIG. 99.—Overturned limbs of folds, showing the position of shear planes developed according to the law of the strain rhomb.

strain will be promoted on one set, but restrained on the other, by the dragging effect produced by the displacement of the adjacent stratum toward the anticlinal axis. The two sets of partings will, therefore, be unequally developed. We may designate the easier partings by 1, and the less obvious by 3. The latter may be wanting, in which case the systems reduce to 1, 2 and 4. Their implications as regards the direction of displacement of the strata, which moved toward the anticline or syncline, are obvious.

The mathematical principles of the strain ellipsoid and of the maximum shearing stresses are sound and should be applied to all cases where they fit. It is desirable, however, to note that like other mathematics they lead to erroneous conclusions if founded on false assumptions. In order that the position of a stratum in a fold shall be correctly determined from joints, the action of the forces which produced the joints must be correctly inferred.

Minor folds, occurring on the flanks of

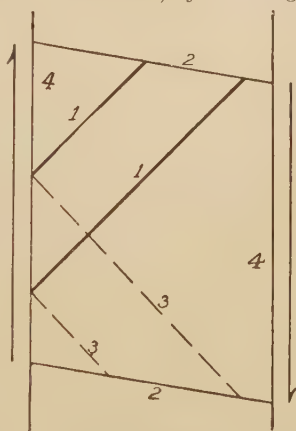


FIG. 100.—Strain rhomb with shearing under compression superimposed upon it. 1-1, most obvious system; 2-2, less obvious system; 3-3, least obvious system, possibly wanting.

larger ones, are commonly similar in form and pitch in the same direction as the major folds. This was brought out by Dale in studies of Mt. Greylock.¹ The application is obvious. The similarity of larger and smaller folds, so long as they developed under similarly oriented stresses, extends to microscopic structures.

Cleavage or schistosity is usually unequally developed in different parts of folds. It is more predominant in synclines than on anticlines and in the middle limb than in the outer ones. So far as this generalization applies to the axial sections of folds, it rests upon the assumption that the anticline corresponds to the outer, convex part of the curve, whereas the syncline is seen as the inner, compressed bend. This would be true of *concentric* folds in all kinds of strata, but concentric folds do not often, if ever, occur where the compression has gone so far as to produce schistosity. In *similar* folds it is desirable to distinguish between the competent and incompetent elements. A competent stratum most clearly exhibits the difference between the anticlinal and synclinal sections, the stratification being better preserved in the former, the schistosity better developed in the latter. The incompetent layers may be confusedly distorted and cleaved within the arch of a competent anticline and therefore do not express the structures clearly.

Where formations of similar lithologic composition form parallel and adjacent belts, which, however, differ in the degree of schistosity, the more schistose belt may represent the overturned middle limb of a closely compressed fold. The inference rests upon the assumption that that limb has been sheared between the other two. The proof is to be sought by tracing the structures along the strike. In the direction of the downward pitch of the axis, the schistose formation may wedge out under a more complete arch or may pass into a thrust-fault. Up the pitch the structure may widen and expose different, deeper-lying formations.

The field investigation of intricate structures must utilize the several methods of attack which have been outlined, together with all the aids of paleontology and petrography which the conditions may permit. Even in simple structures these give invaluable checks on inferences based on observations of the attitudes and sequences of strata, and in more complex studies they become essential.

It is not within the compass of this work to enumerate details of elaborate researches, such as have been found necessary to the solution of problems of Highland structure or of the Pre-Cambrian. For an understanding of their complexity reference should be made to the works of Peach and Horne, in the one case, and to those of Van Hise and his associates, in the other.

One of the most puzzling examples of all structural geology is that which is presented by the Alps. Among the great contribu-

¹ PUMPELLY, RAPHAEL and DALE T. N. Geology of the Green Mountains. U. S. G. S. *Monograph* XXIII p. 119-203; 1894.

tions to geology which have resulted from a hundred years of study, the works of Albrecht Heim stand out significantly, as presenting most graphically the facts of structure, divested of theory. The peculiarity of Alpine structure lies in the association of enormous overturned folds with major and minor thrusts of great complexity. The currently accepted solution leads to mechanical impossibilities and will no doubt be modified eventually until it conforms to those principles which govern the transmission of stresses and the deformation of rock masses under terrestrial conditions.

The discussion of general surveys has been treated in detail because the methods involved are to a large degree applicable also to reconnoissance and special surveys.

Special surveys are those which have for their object some special phase of the geology, rather than a comprehensive mapping of all the features. They are generally commercial in character, and most problems of economic geology involving structural geology call for this class of work.

A special survey, as the name implies, requires some special knowledge on the part of the geologist, that is, he must be a specialist in the phase of the subject covered by the problem. For this reason the danger lies not in overlooking details, but in concentrating on them to the detriment of the broader phases of the problem. Just as the position of major structures may be indicated by those observed in a hand specimen, so are the minor structures, of economic importance, controlled by the general nature of deformation in the region in question. The student of ores, endeavoring to solve the problem of the fault system of a mine, must know whether the region be one of compression or of extension, and he must also know the direction of the compression, or the trend of the normal faults. The geologist hunting for oil structures will not find competent anticlines in a plateau region marked by monoclinical flexures and normal faults. Thus the specialist must to some extent share in the comprehensive knowledge of the explorer, and reason from the larger features of a region down to the details which are necessary to the solution of his special problem.

We cannot better conclude this outline of suggestions for field studies than by reiterating the recommendation to constantly frame explanations of observed facts, to systematically group the

tentative explanations into hypotheses which must be consistent with mechanical principles, and to submit each hypothesis to the test of new facts, that are intelligently and intentionally sought out as critical proofs of falsity or truth.

The method of multiple hypotheses should be consciously and conscientiously adopted.¹ The difficulty with which this is attended is a good test of a man's fairness in scientific thought.

Scientific method consists in arranging known and related facts according to a definite idea, which shall explain them all consistently. The idea becomes an hypothesis which, like a new acquaintance, we naturally desire to cultivate. Having taken form in our own mind, it is a congenial acquaintance and soon becomes a friend. If permitted, it will become more than a friend and will rob us of our freedom of thought. Most thinkers are sooner or later thus robbed and too often by ideas that are only half true.

Safety lies in numbers. Having framed the first theoretical organism and considered its possibilities, dissect it again, lay the individual parts out, stripped to the bone, and reassemble them to form a different skeleton. It will become a competing hypothesis. Repeat the process. Develop genera, species, and varieties of hypotheses and let the law of the survival of the fittest have unrestricted play among them. Thus, and only thus, can you retain freedom to think according to the facts of Nature rather than according to your own notions.

A great geologist said to me recently: "For more than 25 years I have consistently pursued the method of multiple hypotheses. One hypothesis, and one only, has met all tests that I could devise. Am I justified in adopting that hypothesis as true?" It is safe to say that the habit of thinking and questioning and thinking further, which has characterized this great philosopher, will always keep him in touch with Truth.

Our field hypotheses are necessarily crude and undeveloped. Nevertheless, they should be cordially entertained and encouraged to multiply, for they have the great advantage over later ideas that they are organized with fresh facts. It is an essential element of good field work that we should develop hypothetical explanations of that which we observe, and observation, coordination, and interpretation should go on constantly.

¹ CHAMBERLIN, The Method of Multiple Working Hypotheses. *Jour. Geol.*, vol. V, pp. 837-848, 1897.

CHAPTER IX

GRAPHIC METHODS AND PRACTICAL PROBLEMS

BY ROBIN WILLIS

Strike and Dip.—*Definition.*¹—The *strike* of a stratum is the bearing of a horizontal trace on the bedding plane. It is measured in degrees from north to east or west, and is designated by this measurement, as: north 60° west, or north 27° east. These are abbreviated as follows: N. 60° W., N. 27° E. Although the strike has two directions, for instance, northeast or southwest, the convention is always to designate it from north.

The *dip* of a stratum is the angle between a bedding plane and the horizontal, measured in a plane at right angles to the strike. Like the strike it is designated in degrees. For a given strike there are two possible directions of dip. For instance if the strike is northeast, the dip may be southeast or northwest. For this reason it is necessary to follow the statement of amount of dip by a statement of direction, as: 30° northeast, or 45° southwest. These are abbreviated to 30° NE. and 45° SW.

The combination of strike and dip defines the exact attitude of the stratum. An *observation* includes these two, and would appear in the notebook with the description of the formation, as follows:

A. T. P. Str. N. 80° E. Dip. 25° SE.

Bedding Planes.—The strike and dip are measured on a *bedding plane*. A bedding plane is the plane which divides two adjacent strata or beds. The recognition of a bedding plane is of importance if an accurate observation is to be taken. The true bedding is often obscure, and apt to be confused with jointing. The criteria stated below indicate the characteristics of each.

Bedding planes appear as planes of parting, or lines of weakness. The rock is apt to be weathered or stained along these lines.

¹Repeated in part from Chapter I,

In this respect they are similar to joints. They are more regular, however, and, as a rule, do not show openings due to displacement, or rough surfaces except where those are caused by original conditions, such as the development of ripple marks.

In general, bedding planes are more continuous than joints. Except in the case of cross bedding or false bedding, they are usually parallel, as nearly as can be judged by eye, with little variation except when sharply folded. Joints are more apt to diverge from strict parallelism, even in extensive and uniform sets.

A sure mark of a bedding plane is a change in the nature of the material on the two sides.

The spacing of bedding planes varies, according to the material, from small fractions of an inch in finely laminated shale to many feet in heavy-bedded sandstones and limestones. The same is true of jointing, except that it rarely occurs very closely spaced in true sedimentary rocks. In slates, however, the cleavage, which is closely spaced jointing, has the appearance of thin bedding.

Certain marks are characteristic of bedding planes. Among these are ripple marks, rain prints, animal and mollusc trails, layers of shells, and other less common marks.

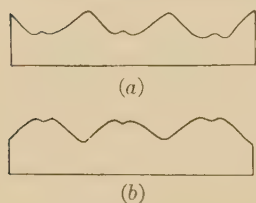


FIG. 101.—*a*. Profile of ripple marks. *b*. Profile of cast of ripple marks. (Modified after a photograph by Van Hise.)

Ripple marks form a series of corrugations and ridges on the surface of the bed. They may be used not only to identify the surface, but to determine which is the upper and which the lower surface. In the normal ripple marks, the ridges are sharp and narrow, the hollows between are wider and smoothly concave, although sometimes there is a minor series of ridges in the middle of the hollow. In the case of the ripple marks on the under side of the bed above, the reverse is true.

Rain prints are found on the surfaces of sandstone beds, sometimes on finer material, and consist of small round depressions dotting the surface.

Animal tracks, fossils, and other criteria are found under special conditions. In case of any doubt as to the direction of bedding, all available means should be used to determine the true direction.

Determination of Strike.—There are three methods of finding the strike of a bedding plane with the Brunton or Gurley compass.

In the first method a smooth surface on the bed, long enough to set the compass on, is necessary. Hold the edge of the compass parallel to the north-south line against the plane, and level the compass. The edge is then in contact with a horizontal line in the bedding plane, and therefore it has the direction of the strike. Read the compass bearing off the needle. (Fig. 102.)

If the bedding plane is too rough, or a smooth portion of one plane large enough to take the edge of the compass cannot be obtained, stand away from the outcrop, choose a prominent bedding plane, and place the eye in the extension of the plane so chosen. Determine the point in the plane at the level of the eye, and sight

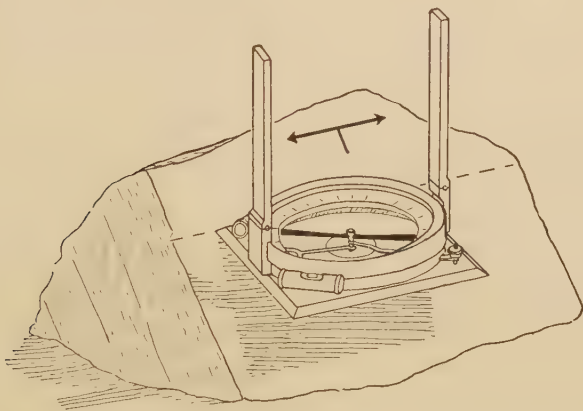


FIG. 102.—Taking the strike. Hold the compass level, as shown, and read the needle.

the compass at this point, as in taking a bearing for a traverse. This direction corresponds with that of the strike.

The second method is more accurate for steep inclinations. In flat-lying beds it is difficult to judge the level line, and a small vertical difference makes a large error in the direction of the strike. This method can be used on outcrops which cannot be reached by other methods.

The third method is useful in flat beds where the exact horizontal line is difficult to determine. Clean off a surface as large as the base of the compass. Lay the compass flat on this surface and turn it until one of the bubbles reads level. The line of the axis of this bubble is the direction of strike, and this line can

be marked, the compass re-oriented on it to give its bearing, and the needle read as above.

Determination of Dip.—To determine the dip of a bed, if the bedding plane offers a smooth and sufficiently large surface, place the edge of the compass parallel to the north-south direction against the plane, with the compass in a vertical position, at right angles to the strike, and read the clinometer. If the compass is a Brunton, the vertical bubble must first be leveled. In the Gurley compass the clinometer consists of a pendulum. This must swing free before being read. (Fig. 103.)

If the bedding plane does not offer a smooth surface, stand away from the bed, sight along the strike as in taking the strike, hold the compass vertically so that the edge parallel to the north-south line lies in the line of sight and is parallel to the bedding plane, and read the clinometer as in the first case.

Record the results immediately in the notebook.

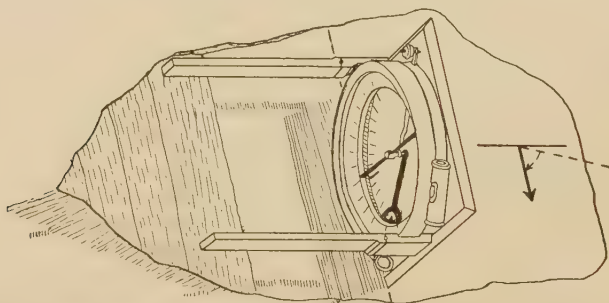


FIG. 103.—Taking the dip. Hold the compass vertical as shown, and read the pendulum or clinometer.

Thickness of Strata.—It is often necessary to find the approximate thickness of strata, without the use of a tape or stick measuring directly across the beds. Such is the case when strata are crossed by a pacing traverse, outcrops located and dips taken, but no accurate measurement made. Two cases arise, namely when the strata are parallel, and when they are folded.

Strata with Uniform Strike and Dip.—In Fig. 104 it is obvious that there are three factors entering into the problem, the distance AB , or outcrop width, the dip, θ , and the thickness BC . If any two are given, the other one may be found, either graphically, or by trigonometry.

For instance, if the outcrop width AB , and the dip θ are given, the thickness can be found by laying off AB , drawing the dip θ at A , and dropping a perpendicular from B to the line of dip at C . BC is the thickness. In the triangle ABC , $BC/AB = \sin \theta$. Hence $BC = AB \sin \theta$. By means of the same equation either the dip or the outcrop width can be found if the other two factors are known.

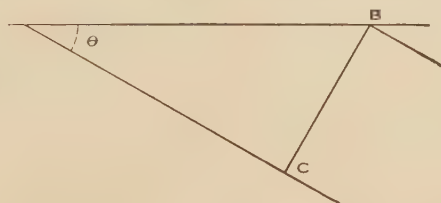


FIG. 104.—Thickness, outcrop width, and dip of strata. Parallel dips and strikes.

If A and B are not at the same elevation, however, a fourth factor is introduced, the difference of elevation, BD (Fig. 105). If this is known, the problem may be solved as above, care being taken, however, to measure the angle of dip from the horizontal, and not from the line connecting A and B . The tangent of the angle α is BD/AD , and $AB = BD/\sin \alpha$. The thickness $BC = AB \sin (\theta + \alpha)$. (Fig. 105.)

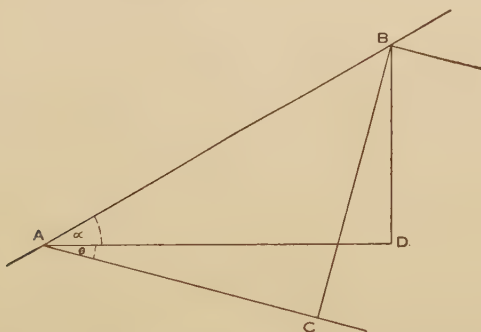


FIG. 105.—Thickness of strata with varying elevation.

Strata with Divergent Dips.—In Fig. 106 are shown two outcrops with parallel strikes, but with dips of unequal magnitudes. The simple solution possible in the preceding case cannot be applied here. In fact, unless certain ideal conditions are assumed, no solution is possible. The ideal condition assumed is that the

fold of the beds between these two points corresponds to the arc of a circle. The solution is indicated in Fig. 106 as follows: The dips are plotted in a section normal to the strike. Perpendiculars are drawn to the dip lines at the points of outcrop. If the dips are not parallel, these perpendiculars must intersect, either below the outcrops, as in Fig. 106*a*, or above, as in Fig. 106*b*. This point of intersection, *C*, is then used as the center of an arc,

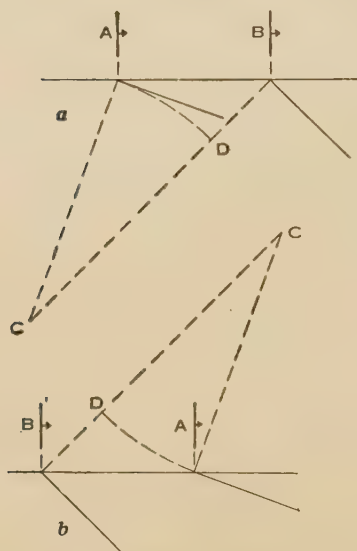


FIG. 106.—Thickness of strata, divergent dips.

swung from the nearer point of outcrop, *A*, and intersecting the perpendicular from the farther point *B* at *D*. *BD* is the thickness of the strata between *A* and *B*.

The limitations of this method are that the folding must be of the concentric type, and that only one limb of the fold can be measured at a time. The closer together the observations the more accurate it becomes, and it fails altogether if there is any considerable change in the curvature of the strata between the two outcrops. Nevertheless, the degree of accuracy that can be obtained with it under normal conditions is amazing.

This method of swinging arcs can be used to considerable advantage in constructing cross-sections of open folds. In any case, however, its limitations must be kept in mind, and judgment exercised in its use.

If the strikes are not parallel, the same method can be used in a few cases to determine the outcrop width, the perpendiculars being drawn from the points of outcrop perpendicular to the strikes, but this is not as generally applicable as the method of finding the thickness.

Descriptive Geometry.—Descriptive geometry is a method of representing on a plane surface objects which have three dimensions in space. It also offers a means for the graphic solution of problems involving three dimensions. As nearly all problems

of structural geology are of this nature, a knowledge of the principles of descriptive geometry is essential to the structural geologist.

There are several divisions of descriptive geometry. Only two of these will be considered here, the two which have the most immediate and practical bearing on geologic problems.

The first of these is called *normal projection*, and involves the projection of objects on two or more planes, at right angles to each other. This is the most useful method for the solution of most geologic problems. Map and section fall under this head. Its drawback is that it does not give the space relations of all three dimensions in one picture, but requires two or more pictures or "projections" to accomplish this.

The other division is called *isometric projection* and involves the projection of objects on a plane inclined to the three major directions and giving a single image showing the three dimensions. In the solution of problems in which the lines or figures considered lie in three planes mutually perpendicular, this method is very desirable. In problems in which the elements are not directly related to three such planes, normal projection is more convenient. Isometric projection, however, is the more useful for purposes of illustration. It has been used for that purpose in this book, therefore an understanding of its principles is desirable, and a brief account is included.

Projection.—The projection of a point on a plane is a point. It is that point at which a line having a given direction and drawn through the original point pierces the plane. The plane is called the *plane of projection*, the direction of the line is called the *direction of projection*.

The same definition can be applied to the projection of a line, a plane, or a solid. In any one projection the direction of projection remains constant.

Normal Projection.—If not otherwise stated, it is assumed that the direction of projection is perpendicular to the plane of projection. This is called normal projection.

Projection on Two Planes.—If the projections of a point on two known planes is known, the position of the point is fixed, provided the two planes are not parallel. (Fig. 107.)

The line of intersection of one plane with another is called the *trace* of that plane on the other.

The trace of one plane of projection on another is called the *folding line*. In normal projection the angle made by two adjacent planes of projection (those having a common folding line) is always a right angle.

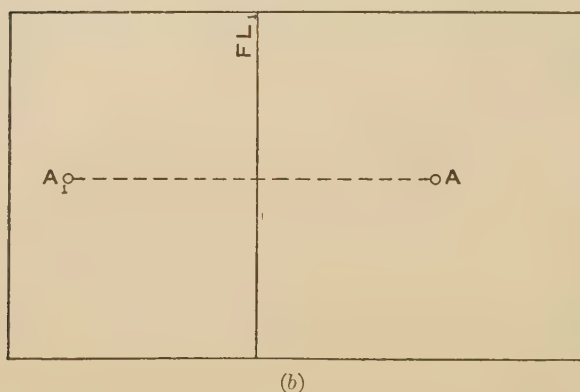
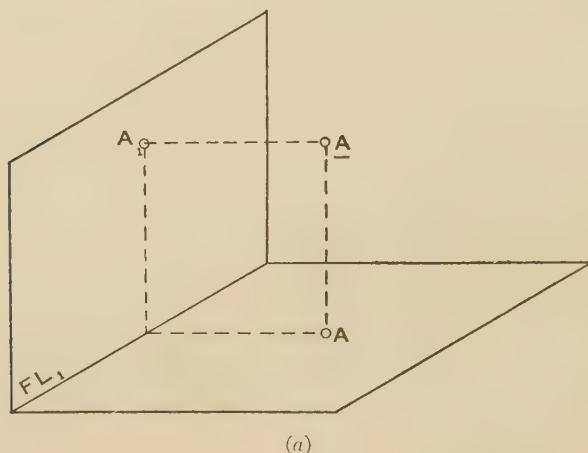
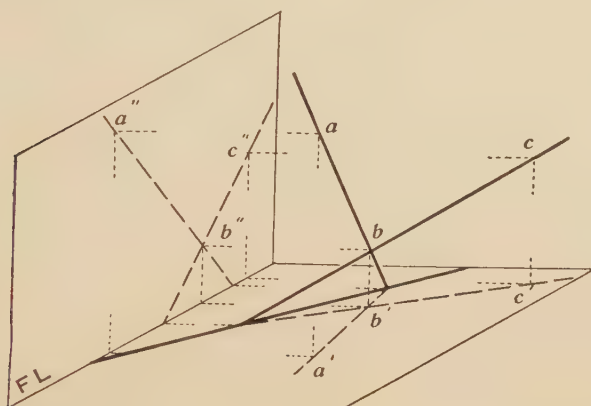


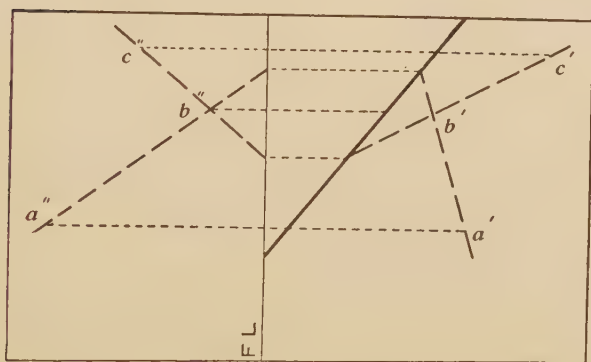
FIG. 107.—Normal projection. *a.* Projection onto two planes at right angles to each other. *b.* The same planes rotated into the plane of the drawing.

In case the contrary is not stated, the first plane of projection is horizontal and is assumed to be in the plane of the paper. This is called the *horizontal projection, plan, or map*. Any adjacent plane of projection must therefore be vertical in normal projection.

This is the *vertical projection*, *elevation*, or *section*. Plan and elevation are the terms used in architecture, map and section are those used in geology.



(a)

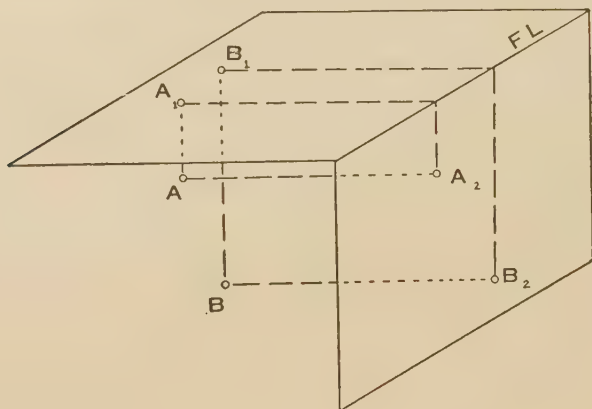


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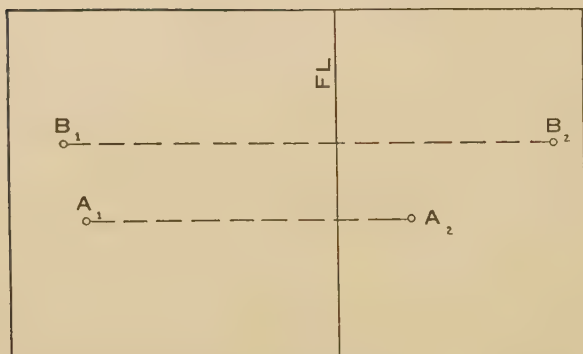
FIG. 108.—Normal projection in the first quadrant. *a*. The projection of two lines and their intersection on two planes at right angles to each other. The heavy line in the horizontal plane represents the trace of the plane defined by the two lines on the horizontal plane. *b*. The same, as it would appear after rotation of the vertical plane into the plane of the paper.

To represent both projections on a flat piece of paper, the vertical plane is rotated about the folding line as an axis, into the plane of the paper. This involves a rotation of 90 degrees. There are

two methods of performing this rotation. If the object to be drawn is placed above the horizontal plane and to the right of the vertical plane, the vertical plane is rotated away from the object, as in Figs. 107 and 108. The effect of this is to put the



(a)



(b)

FIG. 109.—Normal projection in the third quadrant. *a*. Position of planes and object before rotation of the vertical plane. *b*. Position after rotation.

highest point in the vertical projection farthest from the folding line. Thus, in Fig. 108, *a* is higher than *b*, hence *a''* is further from the folding line than *b''*. In geological work, as well as in other sciences using descriptive geometry, it is desirable to have the

higher points nearer the folding line. For instance, a geologic section is generally drawn below the line of section on the map. Considering this line of section as a folding line, it is obvious that the top of the section, the profile of the surface, is next to the folding line. This result is accomplished in descriptive geometry by placing the object under the horizontal plane and to the left of the vertical plane, projecting it upward and to the right. The vertical plane is then rotated away from the object as before, but the object appears with its upper points nearest the folding line, as desired. (Fig. 109.) Point A is above point B , and A_2 is nearer the folding line than B_2 . This is called *third quadrant projection*, because the object is placed in the third quadrant. The method illustrated by Figs. 108 and 109 is known as first quadrant projection. Except in Problem 1, where first quadrant is used for better illustration, third quadrant projection has been used throughout this chapter.

A plane of projection does not have to be either horizontal or vertical. If a folding line is taken between the vertical projection and some other plane, and if this folding line is not parallel or perpendicular to that between the horizontal and vertical planes, the third plane will be oblique to both these directions.

In geology the terms *strike* and *dip* are used to describe the attitude of a plane. The strike of a plane defined, in terms of descriptive geometry, is the direction of its trace on the horizontal projection. The dip is the angle it makes with any horizontal plane, measured at right angles to the strike.

Principles of Normal Projection.—1. The line connecting the projections of a point on two adjacent planes of projection is perpendicular to the folding line. (See Fig. 107.)

2. The vertical projection of a point is as high above the folding line as the point is above the horizontal plane. This is true for all possible vertical planes on which the point may be projected. Hence the height of any two vertical projections of a point above the folding lines between their planes and the horizontal is the same.

This principle may be stated more generally as follows:

In any two planes of projection adjacent to the same plane the distances of the projections of a point to the respective folding lines between these planes and the common plane will be equal.

The two preceding principles enable us to take a folding line in

any direction whatever, and to locate the vertical projection of a point in the corresponding plane, provided the horizontal projection and any one vertical projection of the point are given. This holds true likewise for any three adjacent planes of projection.

Abbreviations and Conventions.—In the problems in this book the following abbreviations and conventions will be followed:

Points will be designated by capital letters, as: *A*, *M*.

Lines will be designated by their terminal points, as: *AB*, *MN*.

Planes other than projection planes will be designated by underlined capitals, as: *A*, *F*, *P*.

Areas in planes will be designated by the points on their boundaries, as: *ABCD*, *MNP*.

Angles will be designated by small letters, as: *a*, *b*, *c*.

Planes of projection will be designated as follows: the horizontal projection will be called *H*. All points in it will be given a letter without a qualifying number. All vertical planes will be called sections, and numbered in order. The folding line between them and the horizontal will be designated *FL* and given the same number, as, *FL*₁ between *H* and Section 1. If a plane is taken which is not a section, it will be numbered in turn, and its folding line likewise. Any projections except those on *H* will carry the original letter, qualified by the number of the section or projection plane, as *A*₁, *B*₃.

Practical Problems.—The following problems are introduced to show the method of normal projection and its application to the solution of problems arising in structural geology:

PROB. 2. To find the true length of a line. Fig. 111.

Given: Two projections of a line, AB and A_1B_1 . To find the true length of AB .

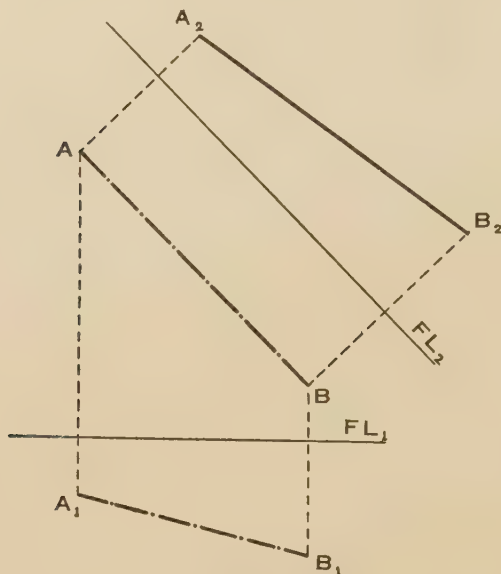


FIG. 111.—To find the true length of a line.

Solution

Take FL_2 parallel to AB .

Find A_2B_2 by the method of Problem 1.

A_2B_2 is the true length of AB , because the third plane of projection is parallel to the line in space, hence the projection of the line on it must have the same length as the line itself.

PROB. 3. To find the dip and strike of a plane. Fig. 112.

Given: Three points, A , B , and C , in a plane, and the elevation of each.

To find: The Strike and Dip of the plane.

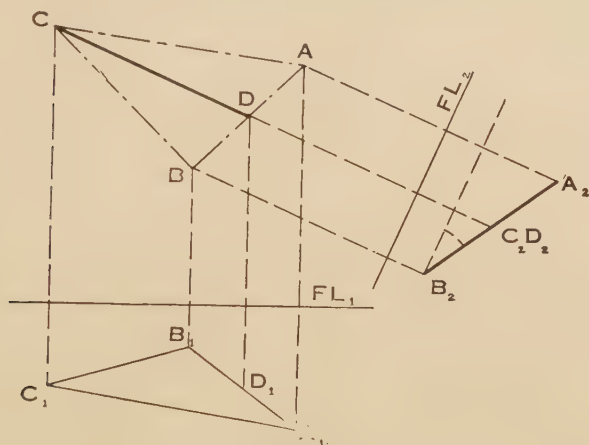


FIG. 112.—To find the dip and strike of a plane.

Solution:

Take FL_1 in any convenient position. Locate A_1 , B_1 , and C_1 by means of projection and their comparative elevations.

Draw a horizontal line through C_1 cutting A_1B_1 at D_1 .

Project D_1 back into H , locating D on AB .

Draw CD . The direction of CD is the strike of the plane, as it is a horizontal line in the plane, because C and D have the same elevation.

Take FL_2 perpendicular to the strike (to CD). Locate A_2 , B_2 , and C_2 . These three points will lie in a line. The angle this line makes with the horizontal (FL_2) is the dip of the plane.

PROB. 4. To plot a dip in a section not at right angles to the strike. Fig. 113.

Given: Plane P with known strike, outcropping at A , and dip a ; FL_1 .

To Find: The trace of P on Section 2.

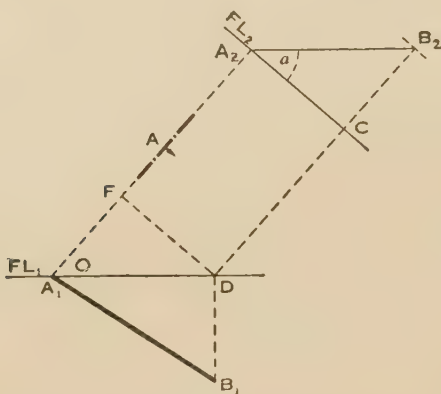


FIG. 113.—To find the apparent dip of a plane in a given section.

Graphic Solution:

Take FL_2 normal to the strike.

Plot the trace of P on Section 2 by means of A_2 and the dip a . Draw a line at some convenient distance below FL_2 , cutting the trace of P_1 and B_2 .

Draw a line perpendicular to FL_2 , from B_2 , cutting it at C .

Continue this line through C to cut FL_1 at D . This line is parallel to the strike (as FL_2 was assumed perpendicular to the strike) and may be considered as a contour on P at the assumed distance below the outcrop A .

From A extend the strike to cut FL_1 at A_1 .

From D drop a perpendicular to FL_1 and locate B_1 at distance B_2C below D .

Draw A_1B_1 . This is the trace of P on Section 1.

Trigonometric Solution. Let ϕ represent the angle between the strike and FL_1 .

Draw a line perpendicular to AA_1 cutting it at F . In the triangle A_2B_2C : the angle $A_2 = a$; the angle $C = 90$ degrees.

Therefore: $A_2C = \frac{B_2C}{\tan a}$.

In the triangle A_1DF : the angle $A_1 = o$.
the angle $F = 90$ degrees.
 $DF = A_2C$.

Therefore

$$A_1D = \frac{DF}{\sin o} = \frac{B_2C}{\sin o \tan a}.$$

In the triangle A_1B_1D : the angle $D = 90$ degrees. $B_1D = B_2C$.

Therefore:

$$\begin{aligned} \text{Tangent of angle } DA_1B_1 &= \frac{B_1D}{A_1D} \\ &= \frac{B_2C \sin o \tan a}{B_2C} \end{aligned}$$

$$\text{Angle } DA_1B_1 = \sin o \tan a.$$

This angle is called the *apparent dip* in Section 1. It is of much importance in constructing sections showing geologic structure, when the section is not normal to the strike. Tables showing the value of this angle for varying values of a and o are called dip tables, and are constructed from the above formula. See Appendix I.

PROB. 5. To find the true shape of a figure. Fig. 114.

Given: Horizontal projection of area $ABCD$, and dip a and strike of the plane in which they lie.

To find: The true shape of $ABCD$.

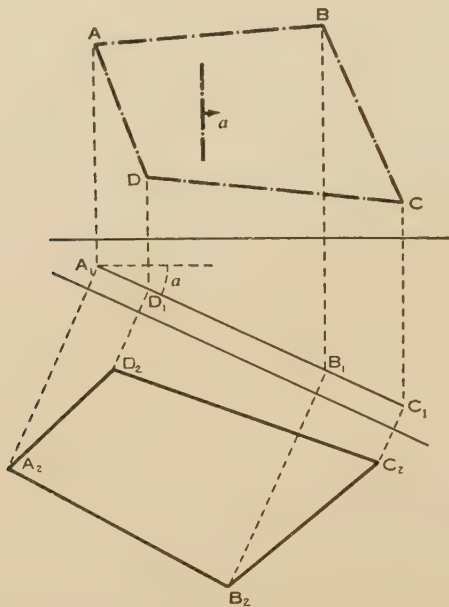


FIG. 114.—To find the true shape of a figure in a plane.

Graphic Solution:

Take FL_1 normal to the strike.

Project A into section 1, assuming an elevation for A_1 .

Draw a line through A_1 making an angle a with FL_1 . This represents the trace of the plane on Section 1.

Locate by projection B_1 , C_1 and D_1 on this line.

Take FL_2 between Section 1 and projection plane 2, parallel to $A_1B_1C_1D_1$. This makes projection plane 2 parallel to the plane of $ABCD$, hence the projection of the figure on it will be in its true shape.

Locate $A_2B_2C_2D_2$ by the method of Problem 1. This is the desired figure.

This problem has a practical application in determining the area of a vein bounded by faults or claim lines, when the dip and strike are known, in order to compute tonnages. It will be seen by inspection that the area $A_2B_2C_2D_2$ is equal to the area $ABCD$ divided by the cosine of the dip a ,

PROB. 6. To find the intersection of two planes. Fig. 115.

Given: Planes $\underline{A}$ and $\underline{B}$, $\underline{A}$ outcrops at A , with known strike and dip a , $\underline{B}$ outcrops at B with known strike, and dip b . The elevation of A and B are given.

To find: The intersection of $\underline{A}$ and $\underline{B}$.

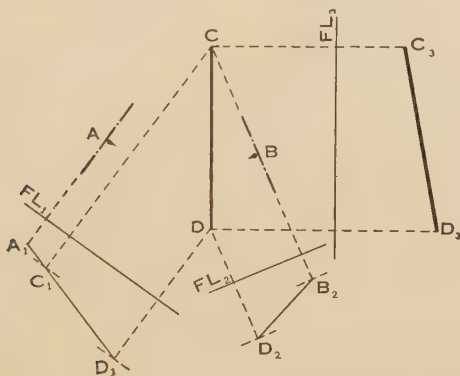


FIG. 115.—To find the intersection of two planes.

Solution:

Take FL_1 normal to strike of $\underline{A}$ and FL_2 normal to strike of $\underline{B}$.

By projection, and their known elevations, plot A_1 and B_2 .

By means of the dips a and b , draw the traces of $\underline{A}$ and $\underline{B}$ on Sections 1 and 2 respectively.

In Section 1, locate a point C_1 on the trace of $\underline{A}$, having the same elevation as B . Locate D_1 on the same trace at a convenient elevation below C_1 .

In Section 2, locate D_2 on the trace of $\underline{B}$ at the same elevation as D_1 .

Project D_1 and D_2 back into H , locating D at the intersection of the projection lines. Project C_1 back to intersect the strike line of $\underline{B}$ through B at C .

Draw CD . CD is the horizontal projection of the intersection of $\underline{A}$ and $\underline{B}$.

To find: the dip of the intersection of $\underline{A}$ and $\underline{B}$:

Take FL_3 parallel to CD . Locate C_3 and D_3 as in Problem 1.

The angle between C_3D_3 and FL_3 is the desired angle.

This problem is of importance in determining the areas of veins cut off by faults of known dip and strike.

PROB. 7. To find the direction and amount of displacement on a fault when the direction of movement and the offset portions of a vein are known. Fig. 116.

Given: Fault $\underline{F}$, with dip o ; vein $\underline{A}$ and its offset portion $\underline{B}$, intersecting $\underline{F}$ at A and B , respectively, and both with dip a ; and the direction of displacement on $\underline{F}$, XY .

To find: The amount of displacement on $\underline{F}$.

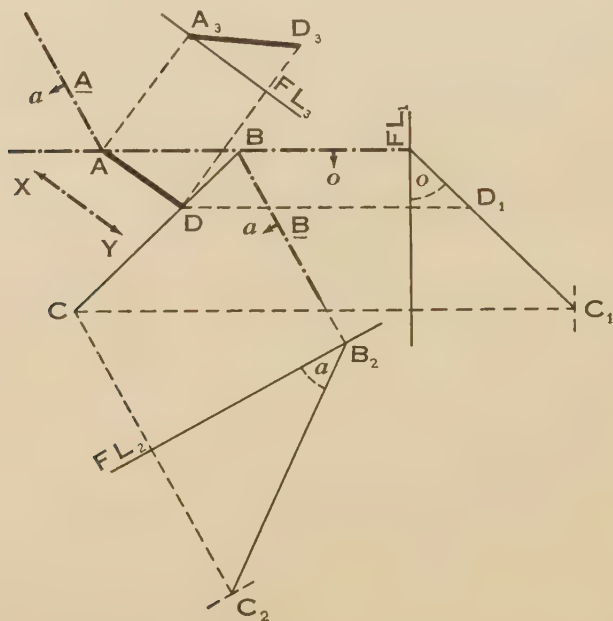


FIG. 116.—To find the displacement on a fault when the direction of movement and the offset of one vein is known.

Solution.

Take FL_1 normal to the strike of $\underline{F}$, and FL_2 normal to the strike of $\underline{B}$.

By the method of Prob. 6 find the intersection of $\underline{F}$ and $\underline{B}$, BC .

From A draw a line parallel to XY , intersecting BC at D . AD is the horizontal projection of the displacement on $\underline{F}$. Project D into Section 1, locating D_1 on the trace of $\underline{F}$.

Take FL_3 parallel to AD , and locate A_3D_3 by projection and Section 1.

A_3D_3 is the amount of displacement on $\underline{F}$.

The practical value of this problem is evident. Many cases arise where a fault cuts off a vein, in which the offset portion of the vein can be located by the above method. By taking sections parallel to the fault, and to the vein, the various components of movement on $\underline{F}$ can be readily found.

PROB. 8. To find the displacement on a fault when the offset portions of two veins are given. Fig. 117.

Given: Fault $\underline{F}$, with dip o ; veins $\underline{A}$ and $\underline{B}$, with their offset portions $\underline{C}$ and $\underline{D}$, intersecting $\underline{F}$ at A , B , C and D respectively. $\underline{A}$ and $\underline{C}$ have a dip a , $\underline{B}$ and $\underline{D}$ a dip b .
To find: the direction and amount of displacement on $\underline{F}$.

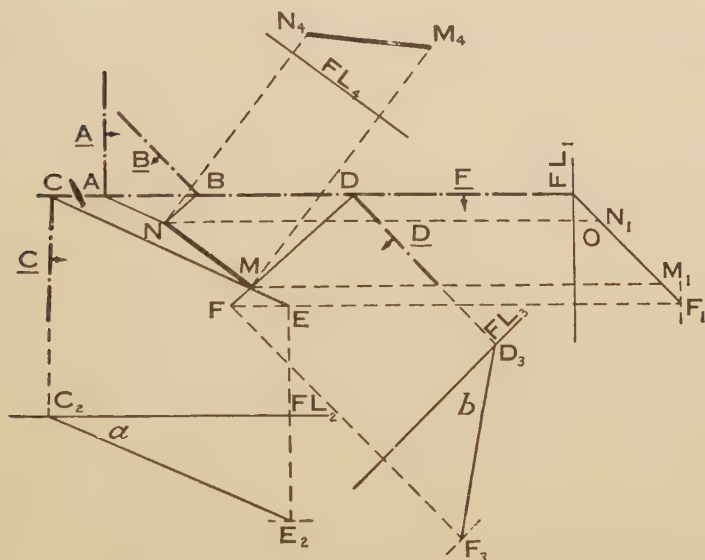


FIG 117.—To find the displacement on a fault when the offset of two veins is known.

Solution:

Take Folding Lines 1, 2 and 3 normal to $\underline{F}$, $\underline{C}$ and $\underline{D}$ respectively, and locate the intersections $\underline{CE}$ and $\underline{DF}$ of $\underline{C}$ and $\underline{D}$ with $\underline{F}$. Continue $\underline{CE}$ and $\underline{DF}$ to intersect in $\underline{M}$. Draw lines through A and B parallel to $\underline{CE}$ and $\underline{DF}$ respectively, intersecting in N . These represent the traces of $\underline{A}$ and $\underline{B}$ on $\underline{F}$.

Draw MN . MN is the horizontal projection of the displacement of A and B on F .

Project M and N into Section 1, locating M_1 and N_1 on the trace of F .

Take FL_4 parallel to MN and locate M_4 and N_4 by means of projection and measurements from Section 1.

M_4N_4 is the amount of displacement on F .

As in the preceding example, the throw, heave, and shift can be determined by taking sections in the proper direction, or by direct measurement in the projections already drawn.

Isometric Projection.—Isometric projection has for its basis the cube. In the cube the bounding planes are considered to lie horizontal and vertical, the four vertical planes striking northeast and southwest. The cube is represented by a single projection in which the direction of projection is that of a line through the upper southern corner of the cube and the lower northern corner. This is a diagonal of the cube. The cube then appears as in Fig. 118, the dotted lines representing the concealed edges of the cube.

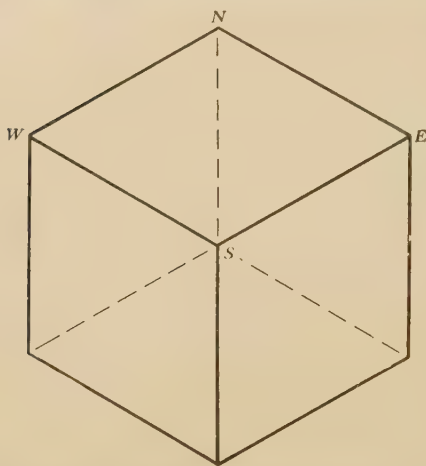


FIG. 118.—The isometric projection of a cube.

This figure is the starting point for all isometric drawings. Certain facts concerning it are apparent from inspection. The chief of these is that the lines radiating from the center, the edges of the cube, form angles of 120 degrees, the hidden edges being rotated 60 degrees from the position of those in front. All the edges are equally inclined to the plane of projection, hence they all appear of equal length in the projection. These facts make the cube very simple to construct.

Fig. 119 shows the method of measuring lines lying in one of the three planes of the cube. With MO as a diagonal, a square $MN'OP'$ is constructed. This is equivalent to rotating $MNOP$,

the upper plane of the cube, into a position parallel to the plane of projection. Hence any line or figure in this plane, which is rotated with it, will appear in its true length or shape after rotation.

Considering the line OP , its equivalent is OP' . As this line lies in one of the three major directions of the cube, all three of which have equal inclinations to the plane of projection, it will be seen that the ratio between OP and OP' is constant for any line in the projection parallel to one of these three directions. This ratio is called the *isometric ratio*, on which is constructed the *isometric scale*. Considering the line MO , it is seen that it is in its true length in the original projection. The line NP , however, extends to $N'P'$, which is a larger ratio than in the case of AB . Therefore we have in the plane $MNOP$ lines with all degrees of shortening, between none at all and the amount shown in NP . The method of finding the length of lines not corresponding to the isometric scale is shown by CD and EF . These two are first extended to cut the edge of the plane; then the point of intersection is projected perpendicular to MO , the axis of rotation, to the edge of the rotated plane.

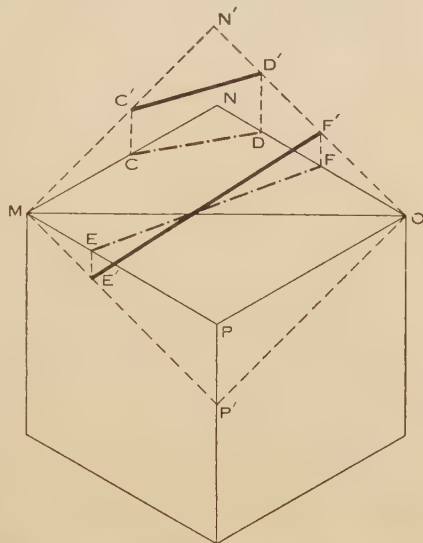


FIG. 119.—Measurement of lines in an isometric projection.

In Figs. 120 *a* and *b* the method of locating the intersection of two planes is shown. Fig. 120*a* shows the method of construction, with the hidden lines dotted in. Fig. 120*b* shows the same figure, without the hidden lines, and with the front portion of the block cut away to one plane, as is done for purposes of illustration.

Some points in the construction may be noted. Where a plane cuts the cube, the trace of that plane on opposite sides of the cube must be parallel. Thus AB and CD are parallel, likewise AD and BC , FG and EH , and so on.

The strike of these two planes is found by rotating the upper plane of the cube, as in Fig. 119, and measuring the angle between AB or FG and the north-south line through the edges of the cube.

A great variety of problems can be solved by this method. As before stated, those problems the lines of which are parallel to the three major directions of the cube are the most easily solved. The aims of this volume however—brevity and simplicity—would both be defeated if any attempt were made to go into the details of such solutions.

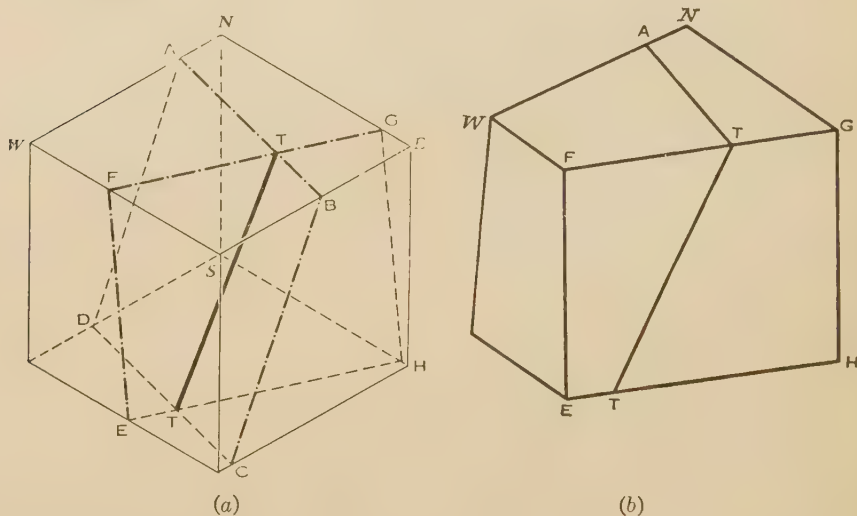


FIG. 120.—Isometric projection of the intersection of two planes. *a.* Construction. *b.* Result, with part of the cube cut away.

One application of the isometric method deserves mention. It may be used to construct accurate relief drawings, to which sections may be added, from topographic maps. The map may be laid off in squares, corresponding to squares drawn in the isometric projection. Points on the map may be located in these squares, and elevations measured above a datum plane, these measurements being made by means of the isometric ratio. Outstanding points so located, valleys, hills and junctions of streams, may then be connected to make the relief diagram.

APPENDICES

APPENDIX I

CORRECTION FOR DIP IN DIRECTION NOT PERPENDICULAR TO STRIKE ¹

Angle of Full Dip	Angle Between Strike and Direction of Section							
	80°	75°	70°	65°	60°	55°	50°	45°
10°	10°	10°	9°	9°	9°	8°	8°	7°
15°	15°	14°	14°	14°	13°	12°	12°	10°
20°	20°	19°	19°	18°	18°	17°	16°	14°
25°	25°	24°	24°	23°	22°	21°	20°	18°
30°	30°	29°	28°	28°	27°	25°	24°	22°
35°	35°	34°	33°	32°	31°	30°	28°	26°
40°	40°	39°	38°	37°	36°	35°	33°	31°
45°	45°	44°	43°	42°	41°	39°	37°	35°
50°	50°	49°	48°	47°	46°	44°	42°	40°
55°	55°	54°	53°	52°	51°	49°	48°	45°
60°	60°	59°	58°	58°	56°	55°	53°	51°
65°	65°	64°	64°	63°	62°	60°	59°	57°
70°	70°	69°	69°	69°	68°	67°	65°	63°
75°	75°	74°	74°	74°	73°	72°	71°	69°
80°	80°	80°	79°	79°	78°	78°	77°	76°
85°	85°	85°	85°	84°	84°	84°	83°	83°

Angle of Full Dip	Angle Between Strike and Direction of Section							
	40°	35°	30°	25°	20°	15°	10°	5°
10°	6°	6°	5°	4°	3°	3°	2°	1°
15°	10°	9°	8°	6°	5°	4°	3°	1°
20°	13°	12°	10°	9°	7°	5°	4°	2°
25°	17°	15°	13°	11°	9°	7°	5°	2°
30°	20°	18°	16°	14°	11°	9°	6°	3°
35°	24°	22°	19°	16°	13°	10°	7°	4°
40°	28°	26°	23°	20°	16°	12°	8°	4°
45°	33°	30°	27°	23°	19°	15°	10°	5°
50°	37°	34°	31°	27°	22°	17°	12°	6°
55°	43°	39°	36°	31°	26°	20°	14°	7°
60°	48°	45°	41°	36°	30°	24°	17°	9°
65°	54°	51°	4 °	42°	36°	29°	20°	11°
70°	60°	58°	54°	49°	43°	35°	25°	13°
75°	67°	65°	62°	58°	52°	44°	33°	18°
80°	75°	73°	71°	67°	63°	56°	45°	26°
85°	82°	81°	80°	78°	76°	71°	63°	45°

¹ Modified after Lahee.

APPENDIX II

Proposition.—The plane of maximum unit shearing stress makes an angle of 45 degrees with the direction of the initial pressure, provided the material sheared is ideally rigid.

Discussion.—Assume a force P acting upon a mass of which $ABCD$ is any cross-section, and take P perpendicular to the surface represented by AB . The pressure P will set up in $ABCD$ a system of stresses radiating in every direction in the mass from the point of application. It is required to find the maximum unit shearing stress, that is, the shearing stress which has the greatest intensity per unit of area of the surface of the shear. (Fig. 121).

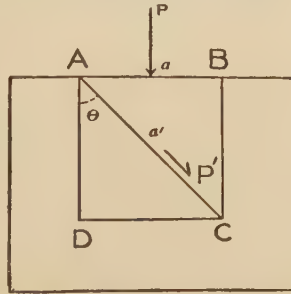


FIG. 121.—Diagram illustrating the law of maximum shear.

Let P equal the initial pressure on a unit of area a . Assume any shearing stress making an angle θ with the direction of P . Let P' represent the shearing stress at that angle. It is distributed over the area a' and the intensity of the unit shearing stress will be P'/a' .

Now $a' : 1$ as $a : \sin \theta$ and a' equals $a/\sin \theta$.

Also P' equals $P \cos \theta$.

Designate the unit stress by S . Then S equals P'/a' , equals $P \cos \theta \sin \theta/a$.

But by trigonometry, $\cos \theta \sin \theta$ equals $\frac{1}{2} \sin 2\theta$, and a equals 1. Hence: S equals $\frac{1}{2} P \sin 2\theta$. The variable in this equation is the angle θ , which may range from zero to 90 degrees. At either extreme the $\sin 2\theta$ is zero and the shearing stress is zero. But $\sin 2\theta$ is a maximum when 2θ equals 90 degrees or θ equals 45 degrees.

Hence it follows that the unit shearing stress S will have its maximum value in a plane inclined at an angle of 45 degrees to the initial pressure.

APPENDIX III

(The following plates are taken from "Mechanics of Appalachian Structure," by Bailey Willis, 1893.)

PLATE A

Many preceding experiments indicated that initial or consequent dips in the models determined the positions of anticlines. Therefore the SB models were constructed to test the control exercised by dip.

DESCRIPTION OF MODEL 1

Original length, $39\frac{3}{8}$ inches = 1 meter. Fig. *a*.

Width, 5 inches.

Thickness, $3\frac{1}{2}$ inches.

Layers	Composition (Parts by Weight)			Thick- ness Inches	Charac- ter
	Wax	Plaster	V. Tur- pentine		
1.....	1	1	0	$\frac{1}{2}$	Hard
2 to 13 (inclusive).....	1	1	0	$12 \times \frac{1}{8}$	"
14.....	1	0	$\frac{1}{2}$	$2\frac{1}{2}$	Soft

The soft base was cut to the form shown in Fig. *a*, and the hard layers were placed upon it under a load of 1,100 pounds and allowed to stand two hours. They then conformed to the initial dips required by the base, Fig. *a*, with the marked change in dip 6 inches from the applied force.

Under uniformly distributed load of 1,100 pounds, equal to about $5\frac{1}{2}$ pounds per square inch of original length, the model was compressed three times, as shown in Figs. *b* to *d*.

Results

An anticline was formed with the acute crest of the arch coincident with the upper line of initial dip. The anticline was competent, as shown by the tunnel within it, and continued compression closed it, forming a carinate fold, Figs. *b*, *c*, and *d*.

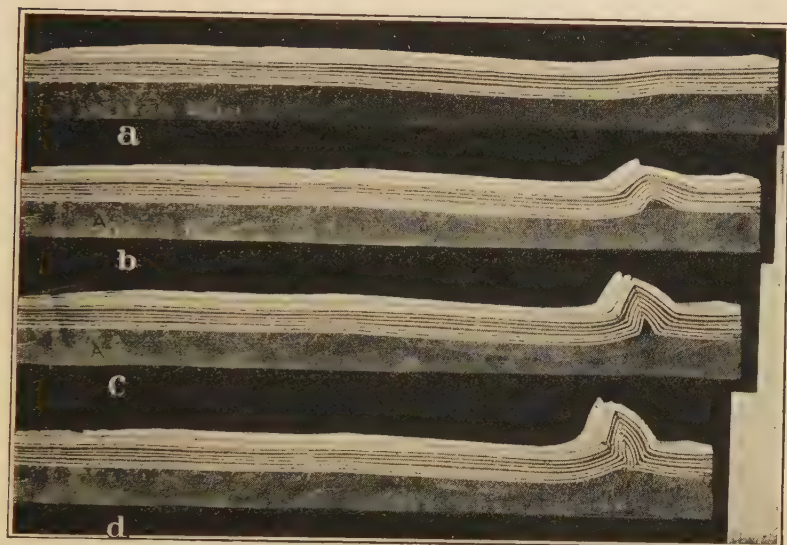
DESCRIPTION OF MODEL 2, FIGS. *a'* AND *b'*

This model was constructed of the same materials and after the same manner as the preceding, but with the line of the initial dip at 18 inches, or three times the distance from the applied force.

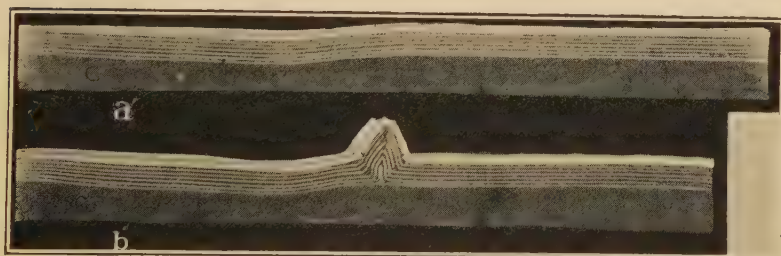
It was compressed once, under load like the preceding.

Results

An anticline, similar in form to that obtained in Model 1, rose at the line of assumed dip.



1



2

PLATE A

PLATE B

DESCRIPTION OF MODEL

Original length, 30 inches. Fig. *a*.

Width, 6 inches.

Thickness, 5 inches.

Layers	Composition (Parts by Weight)			Thick- ness	Charac- ters
	Wax	Plaster	V. Tur- pentine	Inches	
1	1	2	0	$\frac{1}{8}$	Very hard
2	1	0	$\frac{1}{2}$	1	Soft
3 to 14 (inclusive)	1	1	0	$12 \times \frac{5}{32}$	Hard
15	1	1	0	1	"
16	..	0	$\frac{1}{2}$	1	Soft

The model was designed to show the nature of a fold in a series composed of a thick hard bed (15) underlying a number of thin beds. Under a uniformly distributed load of 500 pounds, equal to $2\frac{3}{4}$ pounds per square inch on the original length, it was compressed, as shown in Fig. *b*

Results

Figure *b*. The thick, hard stratum (15) formed an anticline 10 inches from the applied force and broke on the axis. The overlying thin, hard strata were carried up on this anticline and assumed a flat position between it and the load, with steep dips on either limb. The weight borne by the steeper limb of the anticline squeezed the soft layer (16), and this effect, combined with a scarcely noticeable initial dip in Fig. *a*, caused a second anticline to commence at $7\frac{1}{2}$ inches from the resistance. The soft layers flowed into these arches.

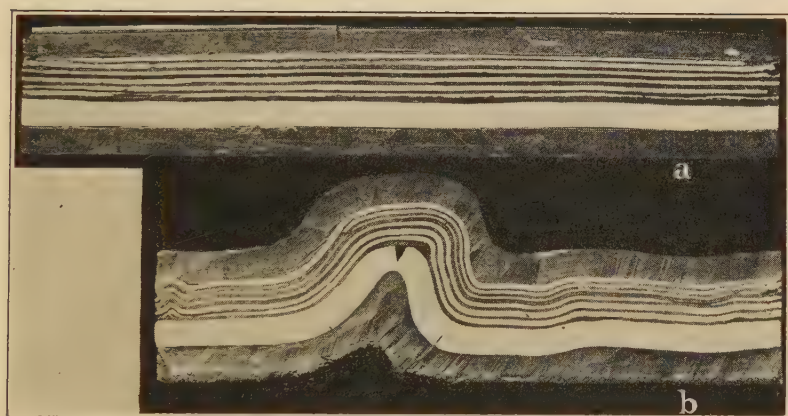


PLATE B

PLATE C

DESCRIPTION OF MODEL

Original length, $26\frac{1}{2}$ inches (not shown).

Width, 6 inches.

Thickness, $2\frac{7}{8}$ inches.

Layers	Composition (Parts by Weight)			Thick- ness Inches	Charac- ter
	Wax	Plaster	V. Tur- pentine		
1.....	1	1	0	$\frac{3}{8}$	Hard
2 to 13 (inclusive).....	1	1	0	$12 \times \frac{1}{8}$	"
14.....	1	0	$\frac{1}{2}$	1	Soft

The model was designed to show the nature of a fold in a series composed of a thick hard bed over many thin hard beds; the difference of thickness assumed was moderate.

Under a uniformly distributed load of 500 pounds, equal to about 3.15 pounds per square inch on the original length, it was compressed four times.

Results

Figure *a*. The hard strata (1 to 13 inclusive) forming a thick but weak series, did not rise in a clearly competent anticline with this degree of shortening; but the soft layer (14) swelled and gave them an initial arch of flat crown, which exceeded the competent dip-length.

Figure *b*. The pressure transmitted upward through the nearer limb of the initial arch raised it and formed a flat but competent anticline. The weight borne by the further limb of the anticline squeezed the soft layer (14) and gave rise to subsequent dips and the beginning of the consequent anticline. There is slight curvature of the strata near the resistance.

Figure *c*. The first anticline is nearly closed in carinate form; the second has developed with a sharp crest and a small keel in the lowest hard layer (13), showing that it was competent, but was nearly filled by the flow of soft material from the region of increased weight to that of relief from load. The soft base has thickened near the resistance and has produced initial dips in the hard strata, which arch over a small tunnel, showing the beginning of a competent anticline.

Figure *d*. The folds previously determined are developed to closing without other deformation. The steeper dips throughout the whole series are toward the lower synclines and are directed both toward and away from the applied force.

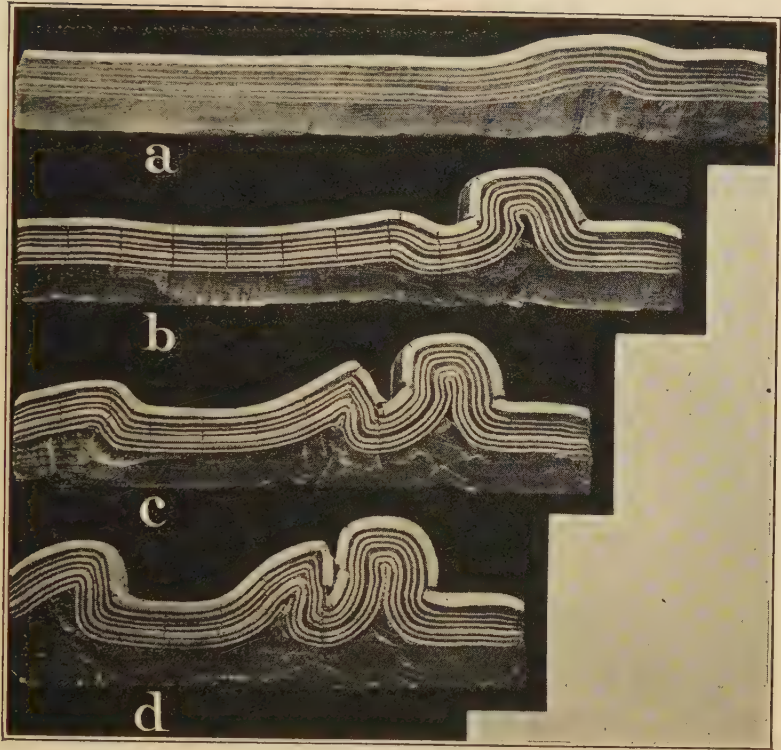


PLATE C

PLATE D

DESCRIPTION OF MODEL

Original length, $39\frac{3}{8}$ inches = 1 meter. Fig. *a*.

Width, 5 inches.

Thickness, $2\frac{1}{2}$ to $3\frac{1}{2}$ inches.

Layers	Composition (Parts by Weight)			Thick- ness Inches	Charac- ter
	Wax	Plaster	V. Tur- pentine		
1 to 12 (inclusive).....	1	1	$\frac{4}{9}$	$12 \times \frac{1}{16}$	Soft
13.....	1	1	$\frac{4}{9}$	$\frac{1}{2}$	"
14 to 17 (inclusive).....	1	1	$\frac{4}{9}$	$4 \times \frac{1}{16}$	"
18.....	1	0	$1\frac{1}{2}$	1 to 2	Very soft

Under uniform load of 1,100 pounds this model was compressed six times, in order to test the nature of the consequent development of strata, which it was supposed would be more likely to predominate upon the softer base.

Results

In Fig. *b* there is a thickening of the base and the initial development of two consequent folds. These folds continued to develop with minor contortion, and the second from the applied force became an important carinate anticline with a detached anticlinal core, involving minor folds upon its limbs. The initial dip remote from the force was slowly accented from stage to stage of compression, but did not at any time develop a fold.

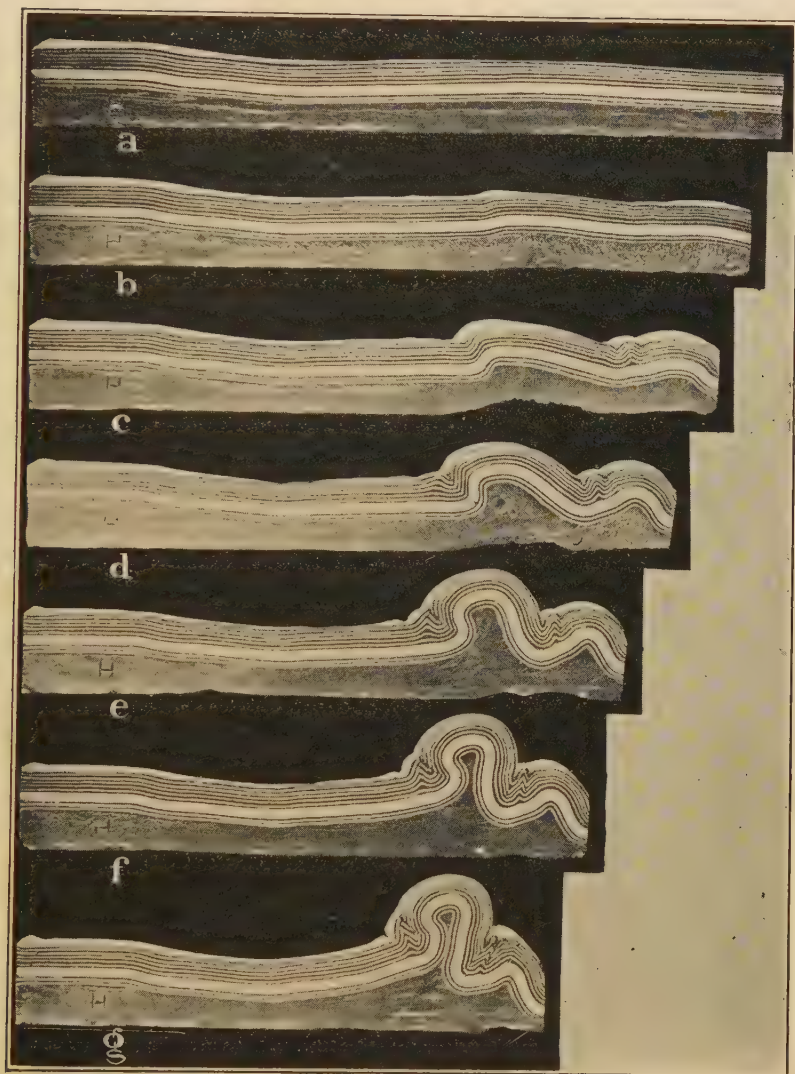


PLATE D

PLATE E

DESCRIPTION OF MODEL

Original length, $39\frac{3}{8}$ inches = 1 meter. Fig. *a*.

Width, 5 inches.

Thickness, $1\frac{3}{4}$ to $3\frac{1}{2}$ inches.

Layers	Composition (Parts by Weight)			Thick- ness Inches	Charac- ter
	Wax	Plaster	V. Tur- pentine		
1 and 2.....	1	1	$\frac{4}{9}$	$2 \times \frac{1}{16}$	Soft
3.....	1	1	$\frac{4}{9}$	$\frac{3}{4}$	"
4 to 7.....	1	1	$\frac{4}{9}$	$4 \times \frac{1}{16}$	"
8.....	1	0	$1\frac{1}{2}$	0 to $1\frac{3}{4}$	Very soft
9.....	1	1	$\frac{4}{9}$	$\frac{1}{16}$	Soft

This model was designed with the intention of removing the influence due to pressure against the soft base and consequent swelling in advance of the piston. The bottom layer was introduced because the thick layer which would otherwise form the base was so soft that the model could not be handled.

Under a uniform load of 1,100 pounds the model was compressed six times, as shown in Figs. *b* to *g*. In Fig. *b* the initial synclinal form is exaggerated, and in Fig. *c* the tendency to depression in the syncline nearest the applied force, which was resisted by the firm base of the box, was deflected upward, causing an anticline upon the slope toward the force. This anticline in turn caused a second fold in advance of it, which became the predominant feature of deformation.

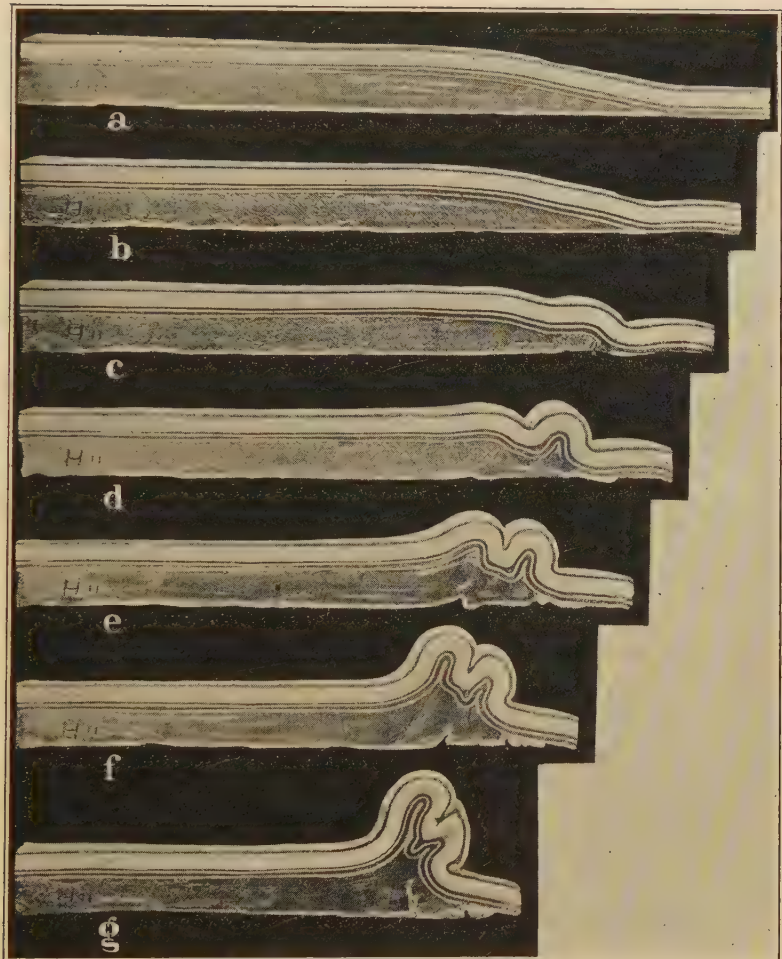


PLATE E

PLATE F

In this model, the strata above the plastic base had the form of a very gentle initial syncline, as shown in Fig. *a*. It was supposed that such a syncline might develop in actual strata in consequence of the deposition of unequal thicknesses, and that the occurrence of greater thickness over the synclinal area might be influential in affecting the character of the folds. In order to test this idea several models were constructed, and pressure was applied to the synclines from different ends.

DESCRIPTION OF MODEL

Original length, $39\frac{3}{8}$ inches = 1 meter. Fig. *a*.

Width, 5 inches.

Thickness, $3\frac{1}{2}$ to $4\frac{1}{2}$ inches, with syncline of deposition arranged with its axis at 27 inches from the applied force.

Layers	Composition (Parts by Weight)			Thick- ness Inches	Character
	Wax	Plaster	V. Tur- pentine		
1 to 8.....	*1	*1	* $\frac{2}{9}$	1 to 2	Soft but firm
9.....	1	1	$\frac{2}{9}$	$\frac{1}{2}$	“ “
10 to 15 (inclusive)....	1	1	$\frac{2}{9}$	$\frac{1}{2}$	“ “
16.....	1	0	3	1 to $2\frac{1}{2}$	Very soft

* Including the thickness of the syncline.

Under a uniform load of 1,100 pounds this model was compressed six times, as shown in Figs. *b* to *g*.

Results

The original syncline was preserved throughout until the pressure of the piston below the crest of the consequent anticlines pushed in a wedge of folded strata which exaggerated the dip from the applied force. The thickening of the very soft base, in this as in other similar cases, produced two consequent folds near the applied force, the further one of which became the more important and developed into a carinate anticline.

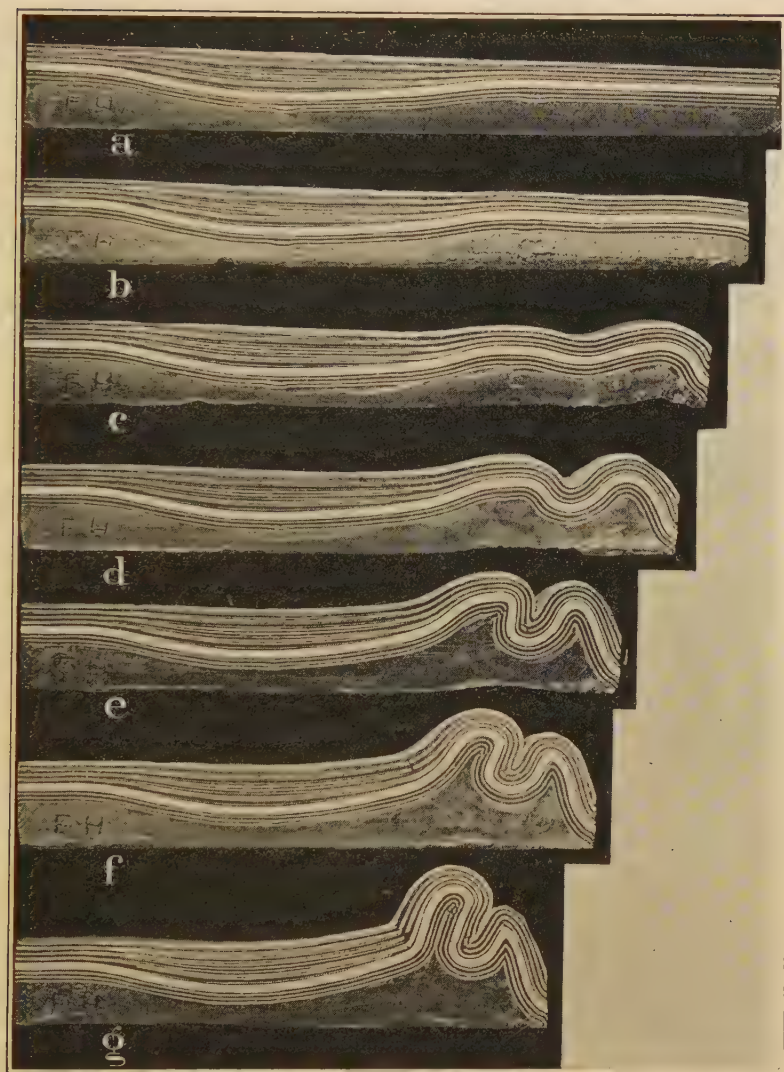


PLATE F

PLATE G

DESCRIPTION OF MODEL V

Original length, $39\frac{3}{8}$ inches = 1 meter. Fig. a.

Width, 5 inches.

Thickness, $3\frac{1}{2}$ inches.

Preliminary pile, full thickness shown at left end.

Layers	Composition (Parts by Weight)			Thick- ness Inches	Character
	Wax	Plaster	V. Tur- pentine		
1 white	1	1	1	$\frac{3}{4}$	Soft, but firm
3 black					
4 white					
5 black					
6 white	1	1	2	$\frac{3}{4}$	Very soft
7 to 12 (13 black).....					
14 white	1	1	3	$1\frac{1}{4}$	Soft as butter at 70° F.
15 to 19					
20 white					

This pile having been made it was cut away on the bottom by a very small amount each time, as many times as there are layers at the right end above the thick white one (1); the cutting was unequal, and gave the bottom at each shaving an uneven surface. After each shaving the model was turned upon its bottom and pressed down on a flat surface, producing in the top a gentle syncline in which a thin layer could be cast. When this was cooled, the bottom was shaved again, the model was again pressed on a flat surface and a second thin layer cast in the new depression. Thus after many shavings and castings the thick white layer (1) was depressed at the right-hand end like a stratum sunk beneath a mass of conformable deposits of unequal thickness, and it extended diagonally through the model with variable initial dips. At the right-hand end the casting consisted of:

Layers	Composition (Parts by Weight)			Thick- ness Inches	Character
	Wax	Plaster	V. Tur- pentine		
1 to 19	1	1	1	$1\frac{1}{4}$	Soft, but firm
20 heavier black } ..					
21 to 42.....	1	1	3	$1\frac{1}{4}$	Soft as butter at 70° F.
1 of left-end white..	1	1	1	$\frac{1}{2}$	Soft, but firm

Under a uniform load of 1,100 pounds the model was compressed nine times, three stages being shown in *c*, *e*, and *g*.

Results

(This represents pressure applied to thick strata in a syncline of deposition.) The initial dips in the principal diagonal layer, extending from the base at the right to the top at the left, controlled the important features of deformation. In Fig. *c* a single competent anticline rose at the nearer initial curve. A small consequent anticline, begun in Fig. *g*, lies beyond this one. The nature of minor deformation was determined by the plasticity of the materials. The soft but firm layers (1 to 20) folded in little anticlines and synclines. The butter-like material folded and also sheared on small fault-planes. The softest material was squeezed from the limbs into the axial regions of the folds.

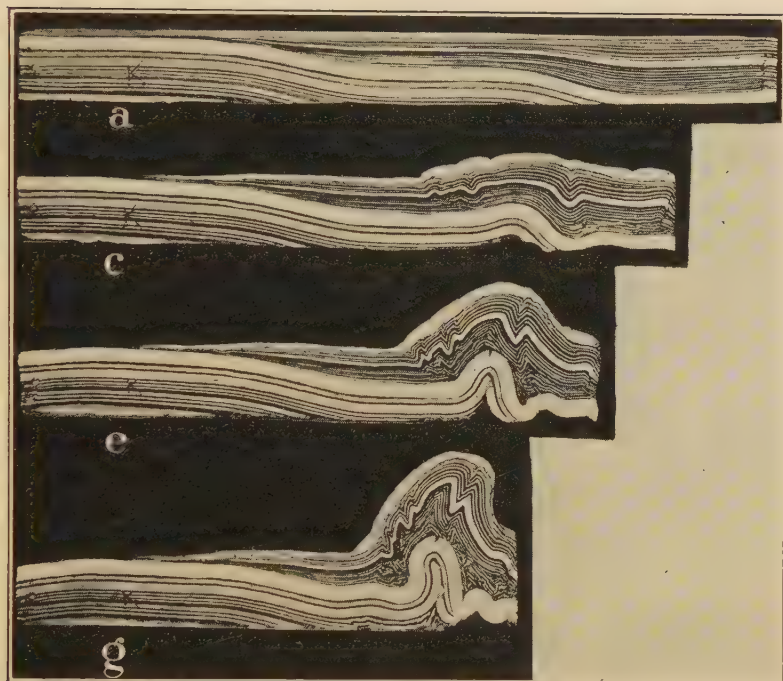


PLATE G

PLATE H

DESCRIPTION OF MODEL

Original length, $39\frac{3}{8}$ inches = 1 meter. Fig. *a*.

Width, 5 inches.

Thickness, $5\frac{1}{2}$ inches.

Preliminary pile, full thickness shown at both ends.

Layers	Composition (Parts by Weight)			Thick- ness Inches	Character
	Wax	Plaster	V. Tur- pentine		
1 black.....	1	1	$\frac{4}{3}$	1	Relatively hard but flexible
2 white } 3 black } 4 white } 5 gray }	1	1	3	$\left\{ \begin{array}{l} \frac{1}{4} \\ 1 \\ \frac{1}{4} \\ 1\frac{1}{2} \end{array} \right\}$	Soft as butter at 70° F.

This pile was shaved unevenly on the bottom, pressed down flat, and filled in until a syncline was formed, Fig. *a*. Then additional layers were cast conformably over the whole length. The material with which the syncline was filled was of the softest character (wax, 1; plaster, 1; V. turpentine, 3). The overlying layers were of varied but firmer composition.

Layers	Composition (Parts by Weight)			Thick- ness Inches	Character
	Wax	Plaster	V. Tur- pentine		
1 to 2.....	1	1	0	$2 \times \frac{1}{4}$	Hardest, frangible
3 to 4.....	1	1	$\frac{4}{3}$	$2 \times \frac{1}{8}$	Hard, but flexible
5.....	1	1	0	$\frac{1}{4}$	Hardest, frangible
6.....	1	1	$\frac{2}{3}$	$\frac{1}{4}$	Hard
7 to 8.....	1	1	$\frac{2}{3}$	$2 \times \frac{1}{8}$	Hard, but flexible
9.....	1	1	0	$\frac{1}{4}$	Hard
10.....	1	1	0	$\frac{1}{4}$	Hardest, frangible

Under a uniform load of 1,100 pounds the model was compressed ten times, three stages being shown in *d*, *g*, and *i*.

Results

This model consisted essentially of the massive, competent layer (1) of the preliminary pile, dipping beneath a syncline of deposition and of an overlying competent series of alternating hard and very hard layers. These two competent members acted independently to a certain degree. In the massive layer the initial dip determined the principal anticline of the lower series, which became overturned from the applied force in the stage shown in Fig. *i*.

The absence of dips in the upper series gave immediate effect to the applied force and produced a double anticline near the end. The competent nature of these smaller folds is shown in the axial thickening of the less hard layers. The soft material filling the syncline served to allow independent movements of the two competent members, and was itself deformed by local pressures and relief from load. The overturn in the lower competent member was determined by the fact that one syncline was deeper than the other and the anticline was free to move in the superincumbent soft mass.

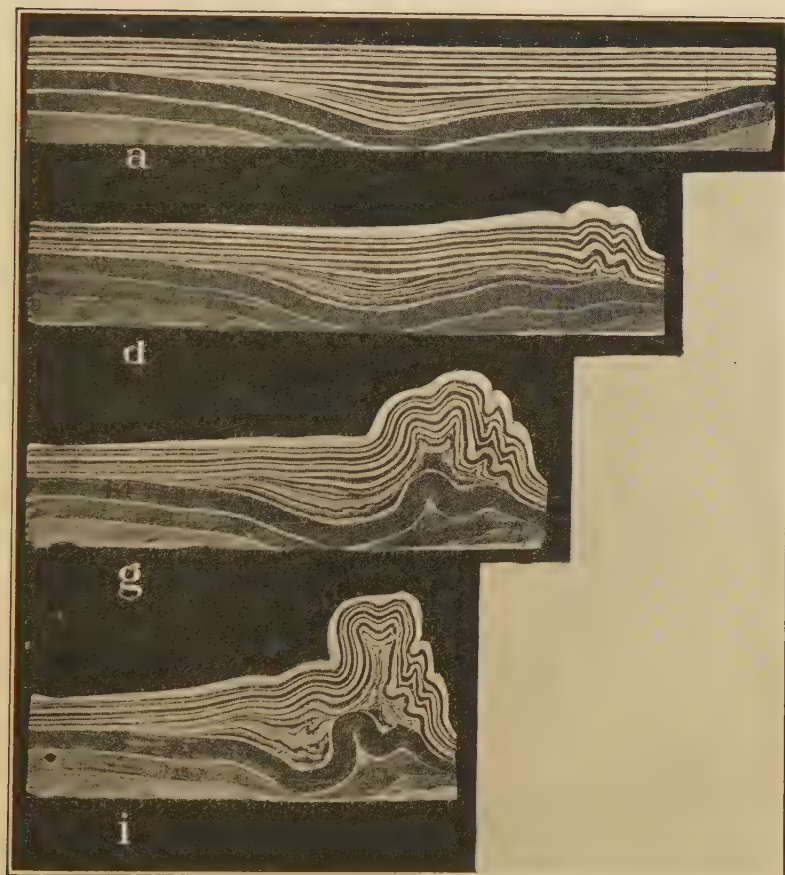


PLATE H

PLATE I

DESCRIPTION OF MODEL

Original length, 27 inches.

Width, 5 inches.

Thickness, $3\frac{1}{2}$ inches.

Layers	Composition (Parts by Weight)			Thick- ness Inches	Character
	Wax	Plaster	V. Tur- pentine		
1 to 4 white and black . .	1	1	1	$4 \times \frac{1}{8}$	Soft, but firm and flexible
5 white	1	1	1	$\frac{1}{2}$	
6 to 8 black and white . .	1	1	2	$3 \times \frac{1}{8}$	
9 yellow	1	1	2	$\frac{1}{8}$	Softer
10 and 11 black and white	1	1	2	$2 \times \frac{1}{6}$	
12 black	1	1	2	$\frac{1}{4}$	
13 green	1	1	3	$\frac{1}{6}$	Softest This material was like but- ter at 70° F.
14 black	1	1	3	$\frac{1}{6}$	
15 red	1	1	3	$\frac{1}{8}$	
16 black	1	1	3	$\frac{1}{8}$	
17 and 18 white and black	1	1	3	$\frac{1}{6}$	
19 purple	1	1-	3	$2 \times \frac{1}{4}$	

This model was constructed to ascertain the nature of deformation in materials of plastic character confined beneath those of firm and flexible nature. The model was compressed under uniformly distributed load of 1,100 pounds, nine times. The sixth and ninth stages are shown.

Results

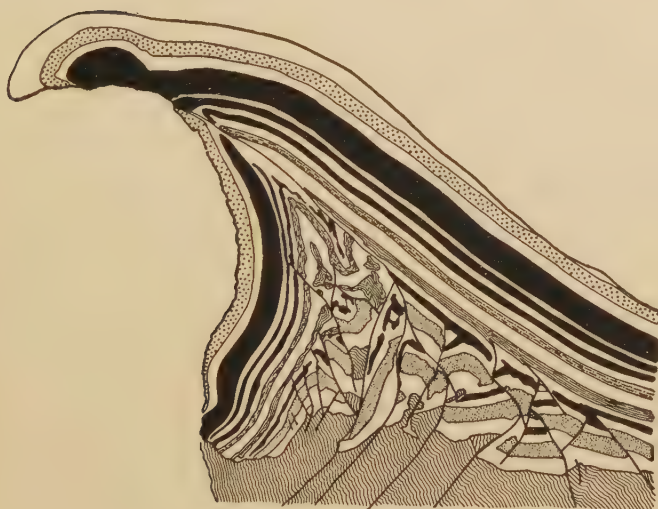
As no initial dips were assumed the position of deformation was determined by swelling near the applied force. In the second stage the arch of the upper strata was entering on development as a competent structure, and the lowest strata were rising into the hollow of the arch by a fault. In this fault the third stage was clearly developed, with clean cut edges, and was confined to the softest, butter-like material, which was relieved of pressure by the overarching competent layers.

As the competent anticline continued to rise the mass of softest material was compelled to change form without change of volume; it was shortened and given space for added height. To this change it accommodated itself by faulting, that is, by flowing on definite planes, not by general flow within the whole mass; the fault-planes divided the mass at first into rhombs, bounded by two faults and two bedding planes, and afterwards into triangular forms, bounded by two faults and one bedding plane. The triangular prisms were so related that the vertical movement in each pair was in opposite directions and the change of form was accomplished as by two wedges moving one against the other. This appears most clearly in Fig. *g*. This faulting may be called incompetent structure in distinction to the growth of the anticline, which is competent structure.

The rise of the competent anticline continued until it overtopped the piston by which pressure was applied. Then the nearer limb of the fold was pushed under the further limb and the strata in the inversion were stretched, producing an overthrust of the alpine type described by Heim—a stretch thrust.



(g)



(k)

PLATE I

PLATE J

DESCRIPTION OF MODEL

Original length, 24 inches.

Width, 5 inches.

Thickness, $3\frac{1}{2}$ inches.

This model was made up of layers which varied in thickness precisely as did those in Plate I; but in this case all the layers were of one consistency, of the softest material that could be handled, composed of wax 1, plaster 1, V. turpentine, 3 parts. This substance resembled butter at 70° F.

The model was compressed under uniformly distributed load of 1,100 pounds, seven times. The figures shown represent opposite sides of the sixth stage.

Results

The material being homogeneous and very soft no layer or series of layers, nor even the whole model, was competent to form an arch which would support the load. Therefore the structures developed were incompetent. The first deformation was by shortening and rising near the applied force, and the adjustment of volume to modified form was by rise of the sections on both sides of a wedge-shaped prism. This deformation produced initial dips, which (to an extent limited by the weakness of the strata) caused the resolution of the pressure into components tangential and radial to the curves. The radial components exaggerated the curvature and new initial dips arose, which had a similar effect. Thus folding ensued, but without competent character. There are no carinate anticlines and the strata are not materially thickened or thinned, except in the case of one lower layer; the thickening there indicates a tendency toward competent development of arches of narrow span.

The model was characterized by striking differences of structure on opposite sides; on the one side the dominant feature is folding, with minor faults; on the other side thrusting developed successively from small folds in a manner very much like Cadell's results in hard materials. It is possible that if the substance had been a little firmer only folding would have developed, and if the substance had been softer deformation would have proceeded by thrusting only.



(g)



(g')

PLATE J

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